K.R. RAMANATHAN

SELECTED PAPERS

INDIAN ACADEMY OF SCIENCES

These two volumes of the Selected Papers of Prof. K.R. Ramanathan were published by the Indian Academy of Sciences on the occasion of his ninetieth birthday.

A founder Fellow of the Academy, and one who occupied its prestigious Raman Chair, he is the most distinguished meteorologist India has produced. He was awarded the International Meteorological Organization Prize in 1961 and was elected President of the International Association of Meteorology in 1954, President of the International Union of Geodesy and Geophysics in 1957 and President of the International Ozone Commission for three terms from 1961-1967.

Professor Ramanathan did his early researches with Prof. C.V. Raman, when he published along with him in 1923 the pioneering paper on the X-ray diffraction of liquids, which is included in this volume. He was one of the earliest members of the team of young scientists who participated in Raman's researches on the scattering of light. But it is as a meteorologist and as one who contributed significantly to the building up of scientific meteorology that he will be remembered most.

These volumes contain his classical papers in the various fields in which he has worked during the last six decades; scattering of light, meteorology, atmospheric ozone, atmospheric physics, geophysics, aeronomy and ionospheric physics. They include his first paper published in 1921 on thunderstorms in Trivandrum, his papers on the distribution of temperature in the first 25 km over the earth, on the general circulation of the atmosphere over India and its neighbourhood and on the Indian south-west monsoon and the structure of depressions associated with it.

His papers on the vertical distribution of atmospheric ozone in low latitudes, on the calculation of the vertical distribution of ozone by the Gotz-Umkehr effect, on the mean meridional distribution of ozone in different seasons calculated from umkehr observations and probable vertical transport mechanisms, his analysis of the ozone observations during the IGY and IGC, his oft-quoted Presidential Address to the International Association of Meteorology at Rome in 1954 on atmospheric ozone and the general circulation of the atmosphere, and the Presidential Address to the International Ozone Symposium in 1964 on the bi-annual variation of atmospheric ozone over the tropics also find a place in these volumes.

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SELECTED PAPERS

OF

K.R. RAMANATHAN

VOLUME I

Prof. K.R. RAMANATHAN

SELECTED PAPERS

OF

K.R. RAMANATHAN

RAMAN PROFESSOR 1980

VOLUME I

A. SCATTERING OF LIGHT
B. METEOROLOGY

INDIAN ACADEMY OF SCIENCES
BANGALORE
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1983

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The diagram, printed on the cover, was prepared by K.R. Ramanathan in 1929 (see page 279) and shows the distribution of temperature in the atmosphere up to 25 km in summer and winter over the northern hemisphere. The diagram showed for the first time that the stratosphere is not isothermal over any particular place and the temperature increases with height above a certain level; Ramanathan also showed that the coldest air over the earth is found above the equator and not over the poles. Ramanathan's diagram retains its validity even today.

The Sanskrit verse on the cover is from *Manu Smriti* (circa 2nd Century B.C.) and is full of meaning to the meteorologist.

"From the sun rain is born;

From rain food, and from food, living creatures"

The picture on the dust cover is of paddy fields in the Valley of Kashmir.

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The Academy would also like to express its gratitude to the Director General of Meteorology, India- Meteorological Department, New Delhi and the Director, Raman Research Institute, Bangalore, for making available many of the journals and volumes from which the papers were reproduced.

FOREWORD

These two volumes of the Selected Papers of Prof. K.R. Ramanathan are being released by the Indian Academy of Sciences on the occasion of his ninetieth birthday. A founder Fellow of the Academy, and one who occupied its prestigious Raman Chair, he is the most distinguished meteorologist India has produced. He did his early researches with Prof. C.V. Raman, when he published along with him in 1923 the pioneering paper on the X-ray diffraction of liquids. He was one of the earliest members of the team of young scientists who participated in Raman's epoch making researches on the scattering of light.

But it is as a meteorologist and as one who contributed significantly to the building up of scientific meteorology that he will be remembered most. His early work was on the thermal structure of the upper atmosphere, when he meticulously obtained data using vultex and rubber balloons and the invaluable Dines meteorograph, resulting in his original discovery that the lowest temperatures in the stratosphere were above the equator and not over the poles. The wind diagrams he produced first for this sub-continent and later the maps of the global circulation of the atmosphere were regularly used by forecasters. His researches on ozone in the atmosphere brought him international fame. He established the ozone observing network in India and proved that in the tropics – unlike in other places – the vertical distribution does not change with seasons. He missed the discovery of the quasi-biennial oscillations of stratospheric winds mainly due to insufficient data, but he was able to show by most careful measurements that the ozone in the atmosphere does participate in this oscillation.

It is interesting that Prof. Ramanathan never left the shores of India until after his retirement from the Meteorological Department at the age of 55. However, the world meteorological community which knew of him and his outstanding contributions to the subject recognised his work by awarding him the International Meteorological Organisation Prize and electing him President of the International Association of Meteorology (when he delivered his classic lecture on atmospheric ozone and the general circulation of the atmosphere). He was also elected President of the International Union of Geodesy and Geophysics in 1957 and President of the International Ozone Commission for three terms starting in 1961.

In spite of his erudition, his scientific achievements and the recognition that he has received, the characteristic that most impresses anyone who meets him is his modesty and humility. I am sure I am speaking for all of the Fellows of the Academy in wishing Prof. Ramanathan many more happy years.

S. Ramaseshan
President
Indian Academy of Sciences
Bangalore

11 February 1983
Bangalore

Prof. K.R. RAMANATHAN with Prof. C.V. RAMAN and Prof. VIKRAM SARABHAI at the 34th Annual Meeting of the Indian Academy of Sciences at Ahmedabad in 1968.

INTRODUCTION

Professor Kalpathi Ramakrishna Ramanathan was born in Kalpathi, Palghat, on 28 February 1893. He had his early education in the Government Victoria College, Palghat and the Presidency College, Madras, from where he took his Bachelor's and Master's degrees in Physics. Professor Stephenson of the Maharajah's College of Science, Trivandrum who was his examiner was so impressed with young Ramanathan that he immediately offered him the post of demonstrator in his Department. During the seven years he worked in Trivandrum he also served as Honorary Director of the Trivandrum Observatory. His first scientific paper was on Thunderstorms in Trivandrum, published during this period. He was to return to meteorology many years later.

He joined Professor C.V. Raman as a University of Madras research scholar towards the end of the year 1921, and collaborated with him in the studies of the molecular scattering of light then in progress in Professor Raman's laboratory in Calcutta. He published ten papers on molecular scattering of light and X-ray diffraction in liquids, gases and mixtures within a period of less than one year and was awarded the D.Sc. degree of the University of Madras for this work.

Domestic responsibilities forced him in 1922 to take up a teaching appointment at Rangoon. Even so, he continued to visit Calcutta during the vacations, and collaborate in the work going on in Professor Raman's laboratory. Three years later he resigned his lecturership at Rangoon to take up the position of Meteorologist in the India Meteorological Department. He retired from the India Meteorological Department in February 1948, on attaining the age of 55 years and soon after joined the Physical Research Laboratory, Ahmedabad as Professor of Atmospheric Physics and its first Director. He retired from the Directorship in 1966, but is still continuing as an Emeritus Professor.

Professor Ramanathan's work in light scattering is well known. During the year he spent at Calcutta, he carried out a series of studies in collaboration with Professor Raman on the intensity and depolarization of light scattered by substances like ether, benzene and carbon dioxide as they passed from the liquid to the gaseous state through their critical temperatures. In addition to these investigations, Raman and Ramanathan also began studies on the role of concentrations of components in light scattering by liquid mixtures and extended their ideas of the fluctuation theory to the understanding of X-ray diffraction by liquids.

It was during his visits to Calcutta on his vacations from Rangoon, that he began work on an intensive examination of the molecular diffraction of light by water. He detected a "weak fluorescence" in the scattered beam, and attributed it to impurities in the liquid. Raman, who was not satisfied with this explanation, felt it was a characteristic of the substance, and his investigations of this "feeble fluorescence"during the next few years led to the discovery of the Raman Effect in 1928.

Professor Ramanathan's research work in the India Meteorological Department covered a wide range of subjects, in each of which he has made basic contributions. Solar and atmospheric radiation, the spectrum of the night sky, meteorological optics and acoustics, terrestrial magnetism, seismology, studies of the Indian monsoon and of storms, depressions and cyclones in the Indian seas, and the general circulation of the atmosphere over India and its neighbourhood were all of equal interest to him. His principal preoccupation, however, was the study of the thermal structure and movements of the upper air, and it is in this field that his contributions are outstanding. He organized the first upper air soundings over India from Agra

using Dines meteorographs and high altitude balloons, and was the first to publish the now famous diagram showing the distribution of upper air temperatures over the world up to 25 km in sumer and winter. It incorporated the valuable sounding-balloon data obtained at a number of stations in India, and a few stations in other parts of the world. This diagram showed clearly the cold and high tropopause over the tropics, and the marked inversion above the tropical tropopause. It also revealed that the coldest air in the atmosphere occurs above the equator, and not the poles. In spite of the immense amount of data gathered since on the upper atmosphere, Ramanathan's diagram still retains its premier place.

Professor Ramanathan established the new Upper Air Division at Poona in 1928, and during the next few years together with his colleagues and research students, he carried out here a comprehensive study of the upper atmosphere over India and its neighbourhood, and also undertook a systematic analysis of the upper winds. His Memoir on the general circulation of the atmosphere over India and its neighbourhood was the first clear and comprehensive study of the subject and is still considered a standard work of reference on the subject.

Prof. Ramanathan's research work at the Physical Research Laboratory was mainly concerned with studies of atmospheric ozone, night airglow, ionospheric and space physics, and solar and galactic influences on the ionosphere. He established the network of Dobson ozone spectrophotometer stations in India, and with his collaborators took the first measurements of the vertical distribution of ozone in the atmosphere over India. With Dave, he evolved and extended the use and development of the Götz Umkehr method of finding the vertical distribution of ozone in the atmosphere.

His major contributions in the study of atmospheric ozone are on the extremely important relationship between atmospheric ozone and the general circulation of the atmosphere, which he announced during his Presidential address to the International Association of Meteorology at Rome, in 1954. The attention attracted by this address led to the establishment of a large number of ozone measuring stations in the world during the International Geophysical Year, and theoretical studies of the behaviour and transport of ozone in the upper atmosphere.

Another important breakthrough in the study of the geographical distribution of ozone was his work on the dependence of ozone distribution on meteorological phenomena such as jet streams and their location, tropopause discontinuities and inter-latitudinal air exchange.

His third major contribution was the discovery of the quasi-biennial oscillation of total ozone in the tropics associated with the 26-month oscillation in stratospheric winds and temperatures, which he announced in his Presidential address at the International Ozone Symposium at Albuquerque in 1964. He also pointed out that the variations in the northern and southern hemispheres are in opposite phases.

Professor Ramanathan has been deeply interested in twilight and airglow studies since 1930. The first airglow spectrum at low latitudes was taken by him in Poona in 1930. This work, continued by him and his students at Poona and later Ahmedabad, Mount Abu, Gulmarg and Srinagar, established the nocturnal and seasonal variations of the green and red lines of oxygen and the effect of solar flares on the green emissions. One of the major contributions, again with Dave, was the estimation of the contribution of secondary and higher order scattering in twilight.

Of importance are also the contributions made by Professor Ramanathan and his students to ionospheric and space studies during the last 30 years, such as the effect of electron-ion collisions in the F-region of the ionosphere on the absorption of cosmic radio noise, and the

effect on the lower ionosphere of X-rays from discrete galactic sources. He considered, long before any one else, the ionosphere as another region where circulation systems similar to those in the lower atmosphere were bound to exist.

He also took an active part in space research both in India and abroad. The successful implementation of the Indian and global meteorological rocket network and the synoptic exploration of the dynamic structure of the upper atmosphere were in large measure due to Professor Ramanathan's support. Of even greater importance in the long term is the interest and support Professor Ramanathan provided for the studies of the interaction between the neutral and electrical atmospheres. His recognition of the thread of unity, which is a principal characteristic of space age atmospheric physics, is possibly the greatest contribution to be attributed to Professor Ramanathan.

Professor Ramanathan has during the last four decades held many distinguished national and international positions connected with research in meteorology and atmospheric physics, hydrology and oceanography and ionospheric and space physics. He was elected President of the International Association of Meteorology in 1954, President of the International Union of Geodesy and Geophysics in 1957, and President of the International Ozone Commission for three terms from 1961–1967.

As President of IAMAP, IOC and IUGG he effectively promoted international co-operation in research in meteorology and atmospheric physics, geophysics and oceanography, hydrology and aeronomy, and the organization of various international observational programmes such as the International Geophysical Year, the International Geophysical Cooperation, the International Years of the Quiet Sun, the International Indian Ocean Expedition, the International Hydrological Decade, and Monex. He played a crucial role in the establishment of the International Meteorological Centre at Bombay during the IIOE, and the formation of the Indian Institute of Tropical Meteorology thereafter.

As a recognition of Professor Ramanathan's contributions to scientific knowledge and his leadership in research, the World Meteorological Organisation awarded him the International Meteorological Organisation Prize in 1961. The Royal Meteorological Society elected him an Honorary Fellow in 1960. The Indian National Science Academy awarded him the Aryabhata medal. He was honoured by the President of India with the award of the Padma Bhushan in 1965 and the Padma Vibhushan in 1975 for his services to science and the country.

Professor Ramanathan is a Founder Fellow of the Indian Academy of Sciences, and served continuously for fifteen years as a member of its Council. The Academy commemorated his sixtieth birthday by publishing a special issue in 1953. Thirty years later, this volume is also being published by the Academy as a tribute to a great scientist, who by his energy and enthusiasm for research inspired many generations of students, and who has had an enduring influence on the growth and development of several scientific fields during the last seven decades, both in this country and abroad.

Anna Mani

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A. SCATTERING OF LIGHT

The Molecular Scattering of Light in Vapours and in Liquids and its Relation to the Opalescence observed in the Critical State.

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1. *Introduction.*

It has long been known that in the immediate vicinity of the critical state, many substances exhibit a strong and characteristic opalescence. In recent years, the phenomenon has been studied by Travers and Usher* in the case of carefully purified CS_2, SO_2, and ether, by S. Young,† by F. B. Young‡ in the case of ether, and in a quantitative manner by Kammerlingh Onnes and Keesom§ in the case of ethylene. An explanation of the phenomenon on thermodynamic principles as due to the accidental deviations of density arising in the substance was put forward by Smoluchowski.‖ He obtained an expression for the mean fluctuation of density in terms of the compressibility of the substance, and later, Einstein applied Maxwell's equations of the electromagnetic field to obtain an expression for the intensity of the light scattered in consequence of such deviations of density. He showed that the fraction α of the incident energy scattered in the substance per unit volume is

$$\frac{8\pi^3}{27}\,\mathrm{RT}\beta\,\frac{(\mu^2-1)^2\,(\mu^2+2)^2}{\mathrm{N}\lambda^4}. \qquad (1)$$

In this, R and N are the gas constant and Avogadro's number per gram-molecule, β is the isothermal compressibility of the substance, μ is the refractive index and λ is the wave-length of the incident light. Keesom** tested this formula over a range of 2·35° above the critical point of ethylene and found good agreement except very close to the critical point.

Of an altogether different order of intensities is the phenomenon of light-scattering in gases and vapours under ordinary pressures observed experimentally by Cabannes†† and the present Lord Rayleigh.‡‡ The effect studied

* 'Roy. Soc. Proc.,' A, vol. 78, p. 247 (1908).
† *Ibid.*, p. 262.
‡ 'Phil. Mag.,' vol. 20, p. 793 (1910).
§ 'Roy. Soc. Proc. Amsterdam,' 1908.
‖ 'Ann. der Physik,' vol. 25, p. 205 (1908).
¶ 'Ann. der Physik,' vol. 33, p. 1275 (1910).
** 'Ann. der Physik,' vol. 35, p. 591 (1911).
†† 'Comptes Rendus,' vol. 160, p. 62 (1915); and 'Ann. de Physique,' vol. 15 (1920).
‡‡ 'Roy. Soc. Proc.,' A, vol. 94, p. 453 (1918).

Proc. Roy. Soc. A. 102, 151–161, 1923.

by these investigators is, in comparison with the phenomenon of critical opalescence, feeble, and requires powerful illumination and special arrangements to enable it to be observed in the laboratory. The measurements made by them show that the magnitude of the effect* is in substantial agreement with the theory of molecular scattering of light developed by the late Lord Rayleigh, according to which the extinction-coefficient α is given by

$$\frac{32\pi^3}{3}\frac{(\mu-1)^2}{n\lambda^4}, \qquad (2)$$

where n is the number of molecules per unit volume. The scattering of light in passage through *dust-free liquids* has also been observed by the present Lord Rayleigh† and W. H. Martin,‡ and it was found by the former that the intensity of scattering in the liquid studied (ether) was considerably smaller than that given by the formula (2), though, owing to the greater density of the liquid, the absolute magnitude of the effect is many times larger than in the vapour.

It is important to notice that these three phenomena, namely, critical opalescence, scattering of light by gases and vapours, and scattering by liquids, which are of such different orders of magnitude, and apparently so distinct, stand in reality in the closest relationship to each other. It has been pointed out by Prof. C. V. Raman§ that the observed scattering power of liquids under ordinary conditions agrees with that calculated from the Einstein-Smoluchowski formula; and further, that this law which reduces to Rayleigh's formula in the special case of a gas obeying Boyle's law, is much more generally applicable than the latter and should be regarded as the fundamental relation determining the magnitude of light-scattering in all fluid media. It thus becomes a matter of great importance to make a thorough test of the Einstein-Smoluchowski formula over the widest possible range of experimental conditions. A series of investigations with this object has been undertaken at Calcutta.

The present paper describes the results of a study made of the scattering of light in ether, both in the liquid and in the saturated vapour phases at different temperatures from 30° up to the critical point 193·6°, and also in the gaseous phase above the critical temperature up to 217° C. Ether was chosen as the first substance to be investigated, because it possesses a high refractivity

* 'Roy. Soc. Proc.,' A, vol. 95, p. 155 (1918).

† 'Roy. Soc. Proc.,' A, vol. 95, p. 95 (1918).

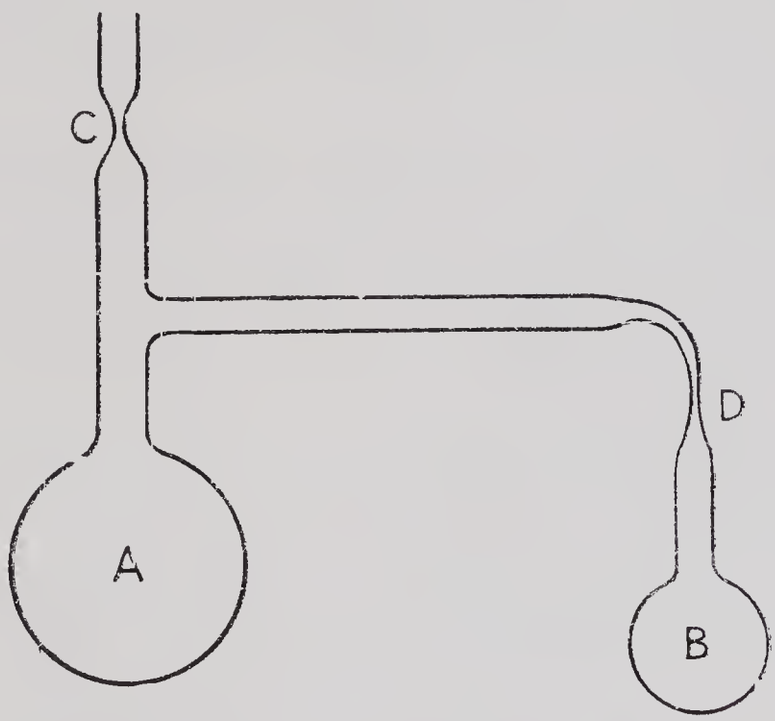
‡ 'Journal of Physical Chemistry,' 1919.

§ 'Nature,' November 10, 1921, and 'Roy. Soc. Proc.,' A, April, 1922. See also "Molecular Diffraction of Light," by C. V. Raman, published by the Calcutta University Press, 1922, pp. 12 and 60.

and hence a large scattering power, is easily obtained pure, and can withstand the action of heat and moderately intense light without appreciable change. Moreover, the classical work of Ramsay and Young* on the pressure-volume relations of the substance over a wide range of temperature provides the necessary data for calculation.

2. *Experimental Arrangements.*

The ether used was Merck's pure ether, redistilled four or five times *in vacuo*. It was contained in a thick, uniform glass bulb of about 3 cm. external diameter. The necessary quantity of ether was introduced into it in the following manner. A glass apparatus of the form shown in the figure was made. The bulbs and connecting tube were well heated over a Bunsen flame and the air exhausted by means of a pump. Nearly four times the required quantity of ether was introduced into the bulbs, and in order to remove the dissolved air, the apparatus was exhausted until more than half



the ether had evaporated and it was then sealed off from the pump at C. All the ether was transferred to the bulb A, and a portion was distilled over into B by placing A in a vessel of warm water at 45–55° C. and B in a vessel of water at the room-temperature (about 30° C.). When B was nearly half filled, its inside was washed out with the distilled ether, which was then transferred back to A without allowing the undistilled ether to come into B. This process was repeated four or five times in order to get the ether perfectly dust-free, and finally, when the required quantity had collected in B, the bulb was sealed off at D.

* 'Phil. Trans.,' A, vol. 178, p. 57 (1887).

The outside of the bulb was painted dead black, leaving three windows, two at the sides to let in and let out light, and one at the base for the observation of the scattered light. It was then mounted in the centre of a thick iron cross-tube, blackened inside, similar to the one employed by Lord Rayleigh (*loc. cit.*). The cross-tube was nearly 1·5 inches external diameter, and each arm of the cross was 7 inches long. Its ends were closed with glass windows, and it could be heated to any temperature up to 250° C. by passing an electric current through a coil of Eureka wire wound uniformly over it. The temperature could be maintained steady within 'less than half a degree for hours. The distribution of temperature was very uniform in the middle of the tube. The tube was mounted horizontally and sunlight was concentrated at the centre of the bulb by means of a lens. Different apertures could be introduced in front of the lens to regulate the quantity of light. Suitable diaphragms were also introduced inside the cross-tube to prevent diffuse light from reaching the eye. With this arrangement the track of the light in the ether vapour was easily visible through the window at the base of the bulb at room temperature when an aperture of 1 inch diameter was in front of the lens.

The intensity of the scattered light was measured by comparing it with the intensity of a similar track in distilled ether kept outside in a rectangular glass bottle. A lens of the same focal length as the one mentioned before was used to produce the track, and suitable apertures were introduced here also to regulate the brightness. The image of the second track was brought into the same field of view by means of two totally reflecting prisms. The prisms exercised very little absorption and the colour-match of the two tracks was practically perfect. The photometry was done with an Abney rotating sectored disc. In order to minimise the heating effect of sunlight, the apertures were made of the smallest size consistent with the visibility of the track, and the light was kept on for as short a time as possible. Temperatures were maintained steady for nearly half an hour before readings were taken.

A correction has to be made for the loss of light on reflection at the glass windows and at the walls of the bulb. It will be noticed that there are six glass-air surfaces and two glass-vapour or glass-liquid surfaces to be taken into account in the case of the bulb, and six glass-air surfaces and two glass-liquid surfaces in the case of the other bottle used as standard. There would thus be an approximate compensation. To test if it is so, and to allow for any absorption which the right-angled prisms might exercise, a comparison was made of the light scattered by the ether in the bulb at room temperature and that scattered by the standard The two were found to be equal within 2 per cent.

3. *Results.*

The observed data for the intensity of the scattering by the saturated vapour in terms of liquid ether as a standard are shown in Table I. The theoretical results indicated by the Einstein-Smoluchowski formula are shown in the third column after applying the correction for imperfect polarisation of the scattered light, as explained below in Art. 5. In order to calculate the theoretical value, it is necessary to know the compressibility, β or $-(1/v\ dv/dp)_t$, and the refractive index, μ, of the saturated vapour at the respective temperatures of observation, and similar data for the liquid used as a standard at 35° C. The compressibilities, $-(1/v\ dv/dp)_t$, of the vapour at different temperatures were determined by plotting Ramsay and Young's pressure-volume data on graph-paper and drawing tangents at the points of saturation. The values of μ were obtained by the application of Lorentz's refraction formula $(\mu^2-1/\mu^2+2) = k\rho$, where k has the value 1/3·317 for ether.

It will be seen that throughout there is a good agreement of the observed and calculated results. In column 4 of Table I, the ratio of the scattering power of the vapour saturated at $t°$ to the scattering power of the vapour saturated at 35°, and in column 5 the ratio of the vapour densities under the same conditions, taken from Ramsay and Young's data, are shown. If Rayleigh's law of scattering had been valid throughout this range, the figures in columns 4 and 5 should have agreed. Actually there is an

Table I.—Scattering by Saturated Ether Vapour.

Temperature ($t°$ C.).	Scattering at $t°$ C. / Scattering by liquid ether at 35° C.		Ratio of scattering at $t°$ C to scattering at 35° C.	Ratio of density of vapour at $t°$ C. to density at 35° C.
	Observed.	Calculated from Einstein-Smoluchowski formula.		
33	0·038	0·036	1·00	0·92
54	0·075	0·074	1·97	1·81
75	0·150	0·140	3·95	3·22
91	0·22	0·23	5·79	4·79
108	0·45	0·45	11·8	7·1
123·5	0·71	0·71	18·7	10·0
144·5	1·31	1·29	34·5	15·7
164	2·7	3·0	71·0	24·0
170·5	3·9	4·0	103	28·0
179·2	9·1	7·9	239	35·3
183·5	13·0	12·2	342	39·8
186·5	21	19	553	44·2
190	42	39	1105	51·9
191	63	55	1658	53·3

enormous difference, showing that, at least in the case of ether, Rayleigh's law breaks down completely, and that the "principle of random phase," on which he founded his theory of molecular scattering, is inapplicable except at very low pressures, where the deviation from Boyle's law is negligible. The scattering power of the vapour is greater, and at the higher temperatures enormously greater, than if the molecules of the gas scattered secondary waves in arbitrary phase-relationships with each other.

The experimental results of the scattering power of ether in the gaseous phase above the critical point are shown in the second column of Table II. In this case, in order to calculate the compressibilities and refractive indices, it is necessary to know the actual mass of ether used, and the volume of the bulb in which it is contained, and these were separately determined at the completion of the experiment, and were found to be 3·164 grm. and 13·98 c.c. respectively. The theoretical value of the scattering power as given by the Einstein-Smoluchowski formula is shown in column 3.

Table II.—Scattering by Ether above Critical Temperature.

Temperature ($t°$ C.).	Scattering at $t°$ C. / Scattering by liquid ether at 35° C.		Ratio of scattering at $t°$ C. to scattering at 35° C.	Ratio of density of vapour at $t°$ C. to density at 35° C.
	Observed.	Calculated from Einstein-Smoluchowski formula.		
194	378	290 at 195°	9950	71·6
196	172	200 at 197°	4530	71·6
198	126			
200	84	87	3316	71·6
202	64	65	1680	71·6
212·5	27	30	710	71·6
217	21	26	553	71·6

Considering the unavoidable experimental uncertainties such as a slight fluctuation of temperature, which has an enormous influence in the neighbourhood of the critical point, the presence of a trace of dissolved air or other impurity in the ether, and the difficulty of determining the value of the compressibility accurately, the agreement should be considered good. The figures in columns 4 and 5 further illustrate the fact that the scattering power of the gas throughout the range of temperature is far greater than would be the case if the "principle of random phase" were valid.

Finally, Table III shows the observed scattering power of liquid ether.

The density data for liquid ether have been taken from Ramsay and Young's paper; the compressibilities below 100° from Amagat's determina-

Table III.—Scattering by Liquid Ether.

Temperature ($t°$ C.).	Scattering at $t°$ C. / Scattering at 35° C.	
	Observed.	Calculated from Einstein-Smoluchowski formula.
33	1·00	1·00
61	1·23	1·34
80	1·85	1·65
91	1·90	1·83
104	2·3	2·13 at 100°
125	3·0	
139	3·8	
145	4·9	8·2 at 150°
153	6·3	
170	12·0	14·1 at 175°
179	22	
185	38	27·2
190·5	82	73 at 190°

tions, and those above 100° from Ramsay and Young's work. There seems to be an inaccuracy in Ramsay and Young's compressibility data for liquid ether at 150°; the values of the pressure and volume do not plot into a smooth curve, and in the curve accompanying Ramsay and Young's paper one can notice an unusually rapid change of curvature in the close proximity of the vapourisation point Making allowance for this, a satisfactory agreement appears between the theoretical and observed values of the scattering power.

Taking the results contained in the three Tables together, it will be seen that the scattering rises rapidly as the critical point is approached, and the values for the saturated vapour, liquid and gaseous phases approach each other and converge to a very large value at this point. The intensity of the scattering under critical conditions is enormous, being about 750 times that of liquid ether at ordinary temperature.

4. *Critical Opalescence.*

The Einstein-Smoluchowski formula (1), as it stands, gives an infinite value for the scattering power at the critical point. This is physically impossible, and both Smoluchowski and Einstein have pointed out that, in the immediate neighbourhood of the critical point, terms involving $(d^3p/dv^3)_t$ and higher order terms should be taken into account. It is, however, doubtful if even the inclusion of these terms would be sufficient, for the scattered light is markedly less blue in this region, which Einstein's

theory does not contemplate. Ornstein and Zernike* have pointed out that the independence of density-fluctuations in different elements of volume assumed by Einstein is inadmissible in this region, and, taking these mutual influences into account, they have deduced a modified equation for the opalescence in which the term $-(dp/dv)_t$ is replaced by

$$-\left(\frac{dp}{dv}\right)_t + \frac{4\pi RT}{v^2}\frac{\epsilon^2}{\mu^2\lambda^2}, \tag{3}$$

where v is the molecular volume and ϵ is a measure of the radius of action of a molecule, beyond which its influence is negligible. Using this, the total fraction of light scattered per unit-volume, instead of being infinity at the critical point, has a finite value

$$\frac{2\pi}{27}\frac{\mu^2(\mu^2-1)^2\ (\mu^2+2)^2}{N\lambda^2\epsilon^2},\ v. \tag{4}$$

Also the proportionality of the scattering light with λ^{-4} gives place to one of proportionality with λ^{-2}.

The change of colour of the opalescent light in the neighbourhood of the critical point, is easily observable when the opalescent beam is reduced in intensity by means of the rotating disc photometer to equality with the scattered light from liquid ether. If we assume that the maximum value of the scattering coefficient is given by (4), we can easily obtain an estimate of ϵ. Observations of the maximum intensity of the scattered light were made by heating the ether about 10° above the critical temperature, and then *very slowly* cooling it. With the particular quantity of ether used (3·164 grm. in 13·98 c.c.) the maximum scattering was found to be 750 times that of liquid ether at 35° C. Putting in the numerical values, and taking λ equal to be 5000 Å.U., the scattering coefficient works out to be $8{\cdot}6 \times 10^{-3}$, and ϵ to be $4{\cdot}6 \times 10^{-7}$ cm.

However, this correction to the Einstein-Smoluchowski formula is of secondary importance, and does not affect the broad aspects of the question.

5. *Polarisation of the Scattered Light.*

It has been shown by Lord Rayleigh, that the light scattered by dust-free gases and vapours in a direction at right angles to the incident beam is, in most cases, imperfectly polarised. In the case of ether vapour, he found that the ratio of the weak component to the strong in the scattered light was 1·7 per cent. It was interesting to study how the imperfection of polarisation changes as the condition of the substance changes from liquid to vapour. At ordinary temperatures, the light scattered by liquid ether showed an

* 'Roy. Soc. Proc. Amsterdam,' vol. 17 (1914), and 'Phys. Zeitschrift,' vol. 18 (1917).

imperfection of polarisation amounting to 8 per cent. As the temperature was raised, it remained constant until a temperature of about 125° was reached and then fell off, rapidly at first, and then more slowly to the value corresponding to that of the vapour at the critical point. Table IV gives the results of the polarisation measurements on liquid ether at different temperatures.

Table IV.—Polarisation of Light Scattered by Liquid Ether.

Temperature.	Weak component compared with strong.
33° C.	8 per cent.
60	8 „
80	7 „
100	7·5 „
120	7·5 „
135	5 „
145	3 „
165	1·7 „
189	1·3 „

In the case of the vapour, measurements of polarisation were made from 160° to about 200° C. The values of the ratio of the weak component to the strong ranged from 1·3 to 1·0 per cent. There was no change in the value of the ratio on passing through the critical point.

The difference between the liquid and the vapour at the lower temperatures is striking. In the case of gases, the late Lord Rayleigh has shown that imperfection of polarisation can be explained on the assumption of asymmetry of the molecules. The increased value for the imperfect polarisation in liquids, and its rapid decrease with temperature, are results of great interest which await explanation.* Further studies on this point, with a number of other vapours and liquids, are being made by the writer.

This imperfection of polarisation has to be taken account of in calculating the intensity of the scattered light. In the case of gases, Cabannes has shown that the scattering is greater in the ratio $6(1+r)/(6-7r)$, where r is the ratio of the weak component to the strong in the light scattered in a perpendicular direction. The question can be viewed in yet another way. The imperfectly

* Since the above was written, a theory based on the conception of molecular æolotropy has been developed by Prof. C. V. Raman, which not only explains these phenomena, but predicts also that the imperfectness of polarisation, both in the case of liquids and vapours, should decrease and tend to a minimum at the critical point. Observations by the writer on benzene confirm this result.

polarised light can be looked upon as being caused by an admixture of a certain quantity of unpolarised light with the polarised light. If to a beam of polarised light of intensity A, there be added a beam of unpolarised light of intensity 2B, the resultant light will be imperfectly polarised and the ratio of the weak component to the strong would be given by $r = B/(A+B)$ and the intensity of the resultant light will be $A(1+2B/A) = A\left(1+\frac{2r}{1-r}\right)$. When r is small this reduces to $A(1+2r)$. An expression of this form is found to agree with the intensity of the scattered light in gases and liquids, when A is taken to be the scattering calculated from the Einstein-Smoluchowski formula. The factor $1+2r/(1-r)$ becomes of great importance when r is large. It will be noticed that when r is not very large, this expression becomes practically equal to the correction factor $6(1+r)/(6-7r)$ introduced by Cabannes. In the Tables I, II and III given above such a correction has been introduced. The imperfection of polarisation for ether vapour has been throughout taken to be 1·2 per cent. and that of liquid has been taken as given in Table IV.

6. *Summary.*

1. Three instances of light scattering by homogeneous media are known; opalescence of a substance near the critical point, scattering of light by gases, and scattering of light by liquids. The present investigation was undertaken to test the view put forward by Prof. C. V. Raman that these phenomena are fundamentally related to each other, and that the intensity of scattering in all these cases should be represented by the Einstein Smoluchowski formula, which is more general than the Rayleigh law of scattering and supersedes it except in the special case of gases obeying Boyle's law.

2. Experiments on the scattering of light by ether, in the vapour and liquid phases at different temperatures from 33° C. up to the critical temperature 193·6°, and in the gaseous phase from 193·6° to 217°, are described.

3. The results are in accord with the Einstein-Smoluchowski formula and not with the Rayleigh law of scattering.

4. The Einstein-Smoluchowski formula is inapplicable in the *immediate neighbourhood* of the critical point. The scattered light is markedly less blue here. Following the theoretical work of Ornstein and Zernike, from the maximum value of the intensity of the scattered light, the value of ϵ the radius of action of an ether molecule is deduced to be $4{\cdot}6 \times 10^{-7}$ cm.

5. The light scattered at right angles to the incident beam is imperfectly polarised; the ratio of the weak component to the strong is throughout nearly 1·2 per cent. in the case of vapour, while, in the case of liquids, the

ratio is 8 per cent. at ordinary temperatures which remains constant till about 120°, and then falls off, rapidly at first and then slowly to about 1·2 per cent at the critical point. There is no change of imperfection of polarisation on passing through the critical point. The correction due to this in the expression for the intensity of the scattered light is given.

In conclusion, I have great pleasure in recording my indebtedness to Prof. C. V. Raman who suggested the research, and who continued to take an inspiring interest in its progress. The experimental work was carried out in the Physical Laboratory of the Indian Association for the Cultivation of Science, Calcutta.

VIII. *On the Molecular Scattering of Light in Dense Vapours and Gases.* *By* C. V. Raman, *M.A., Hon. D.Sc., Palit Professor of Physics in the Calcutta University*; *and* K. R. Ramanathan, *M.A., Demonstrator in Physics, Maharajah's College, Trivandrum, and University of Madras Research Scholar* *.

1. *Introduction.*

As is well-known, the theory advanced by the late Lord Rayleigh † explaining the blue light of the sky as due to the molecular scattering of sunlight has of recent years been amply confirmed by accurate measurements of sky-radiation and of the attenuation of the sun's rays in traversing the earth's atmosphere, and also by the laboratory experiments of Cabannes ‡ and of the present Lord Rayleigh § which have demonstrated the scattering of light by dust-free gases and shown that its magnitude is in agreement with the theory. Apart from its special application to the explanation of the blue light of the sky, the subject of the molecular scattering of light possesses very great interest, standing as it does in intimate relationship with the fundamental problems of optics, such as the propagation of light and the reflexion, refraction, dispersion, and extinction of light in transparent media. Its study has already yielded information which is of first-rate importance in testing theories of atomic and molecular structure, and promises to prove even more fruitful in future in the same direction. It is also not improbable that the study of the problems of molecular scattering of light may serve to elucidate the nature of radiation itself, that is, to determine whether it consists of some form of continuous disturbance moving through space, as contemplated by Maxwell's electromagnetic theory, or whether it consists of discrete entities or "quanta," as conceived of by Einstein. It is proposed in this paper to consider the very important problem of the scattering of light in *dense* media, such as vapours and gases under high pressure, in which circumstances, as was pointed out by the late Lord Rayleigh himself, the simple treatment proposed by him is not applicable. Fresh experimental evidence bearing on the subject will also be referred to.

* Communicated by the Authors.

† Phil. Mag. xlvii. pp. 375–384 (1899). Scientific Papers, vol. iv. p. 397.

‡ *Annales de Physique*, xv. pp. 1–150.

§ Proc. Roy. Soc. xciv. p. 453 (1918) *et seq.*

Phil. Mag. 45, 113-128, 1923.

2. *Rayleigh's Theory of Light-Scattering.*

As a preliminary to the discussion of the problem of light-scattering in highly compressed gases and vapours, it is useful to recall very briefly the principles on which the case of gases under ordinary conditions was dealt with by Lord Rayleigh. Reduced to its essentials, the treatment is on the following lines :—

The individual molecules in a gas through which the primary waves of light pass are regarded as secondary sources of radiation, each molecule acting more or less as it would in the absence of its neighbours. There is, of course, a definite phase-relation between the primary wave when it reaches a given molecule and the secondary wave emitted from it. *In the direction of propagation of the primary waves* the secondary radiations emitted by all the molecules in a given layer are in identical phase, for the differences in the phase of the primary wave when it reaches different molecules are exactly compensated by the acceleration or retardation due to the scattered waves having to traverse a shorter or greater path, as the case may be. *In other directions*, however, owing to the molecules being distributed at random within the volume of the gas, the phases of the scattered waves do not stand in any invariable relation to each other, and hence, in order to find the average expectation of intensity of the scattered light emerging from within the gas, the *intensities,* not the amplitudes of the waves scattered by the individual molecules, should be added up. In all ordinary cases there is very little difference of phase between the primary wave reaching an individual molecule and the secondary wave sent out by it so far as the direction of original propagation of the wave is concerned. When, however, the effect of all the molecules contained in a stratum parallel to the plane of the primary wave is integrated by the usual method of subdivision of the stratum into Fresnel zones, and the resultant is combined with the primary wave, a change of phase appears which may be identified as the retardation associated with the passage of waves through a refractive medium. A relation is thus obtained between the scattering power of the molecules, their number per unit volume, and the refractivity of the medium. Thus, taking the light-vector in the primary waves to be represented by $R_0 \cos(\omega t - lx)$, where x is measured from the position of the scattering molecule, the vector in the scattered wave arising from it may be written as

$$A_1 \cos(\omega t - lr) R_0 \sin\theta / r, \quad . \quad . \quad . \quad . \quad (1)$$

when r is the distance from the molecule and θ is the angle between the vibration at the origin and the scattered ray. On carrying out the calculations indicated, the relation obtained is

$$n_1 A_1^2 = \frac{4\pi^2(\mu-1)^2}{n_1\lambda^4}, \quad \ldots\ldots \quad (2)$$

where n_1 is the number of molecules in unit volume, λ is the wave-length of the light, and μ is the refractive index of the gas.

The energy scattered by the molecules in the interior of the gas must be derived from the primary beam, and hence the intensity of the latter must suffer an attenuation as it passes through the medium. The coefficient of attenuation may be readily evaluated by a simple calculation of the total energy scattered by an individual molecule, and then multiplying this by the number n_1 of molecules per unit volume. We thus obtain the intensity of the transmitted light to be $I = I_0 e^{-kx}$, where k the coefficient of attenuation is given by the relation

$$k = \frac{32\pi^3(\mu-1)^2}{3n_1\lambda^4}. \quad \ldots\ldots \quad (3)$$

This expression for the attenuation coefficient may also be derived directly by a more accurate investigation, which does not neglect the small difference of phase between the primary wave and the secondary waves originating at a molecule. It is then found that on compounding the effects of the primary wave with those of the secondary wave arising from a stratum of molecules, there appears, in addition to the alteration of phase of the primary wave, also a small diminution in its intensity which is exactly that expected in view of the lateral scattering of part of the energy.

3. *Justification of the Principle of Random Phase.*

It will be seen from the foregoing that the Rayleigh law of scattering depends for its validity on the principle that the phases of the waves laterally scattered by the individual molecules are absolutely at random. This point is clearly brought out in the detailed analyses of the problem which have been given H. A. Lorentz * and by the late Lord Rayleigh himself †, and it appears that the necessary random character of the phases of the scattered waves can only arise

* Proc. Roy. Soc. of Sciences, Amsterdam, xiii. p. 92 (1910).

† Phil. Mag. xxxvi. pp. 429–449 (1918).

from a random arrangement in space of the molecules under consideration. If we deny the random character of this distribution of phase of the scattered waves, we must also deny the applicability of Rayleigh's law expressing the intensity of the scattered light in terms of the refractivity of the medium. The fact that even in a gas at atmospheric pressure there are about 10^6 molecules in a cube of the size of a wave-length of light, so that the scattered waves arising from adjacent molecules differ in phase by only 10^{-2} of the period, has been felt as a difficulty by some writers in this connexion. In fact, Larmor * has raised the question whether in view of this closeness of packing we are really justified in considering the phases of the individual scattered waves to be distributed entirely at random. It may be easily shown, however, that no appreciable deviation from a random distribution of phase, and therefore, also, from the Rayleigh law of scattering, can arise so long as the pressure-volume relation of the gas does not sensibly deviate from Boyle's law. For, all that is necessary is that the chance that a given molecule finds itself in a specified finite element of volume should be a random one, that is, is sensibly uninfluenced by the other molecules in the gas. This is true provided the total volume occupied by all the molecules, or rather by all their spheres of mutual action, forms a small fraction of the total space in the containing vessel, which is obviously also the condition that the compressibility of the gas should not appreciably deviate from that given by Boyle's law.

Larmor has made the suggestion † that Rayleigh's principle of random phase is not correct in the form in which it is stated, but that the random character of the phases of the scattered waves when they reach the observer is secured by the Doppler effect, due to the motion of the scattering molecules. The view he proposes is, in fact, that the phases of the scattered radiations emerging from the column of gas may be correlated at first, but after traversing 10^6 wave-lengths, or 50 cms., they would have become fortuitous and the energy-effects thus additive. Larmor's suggestion is, however, not acceptable. For, if it were correct, we should find that the aggregate intensity of the scattered light should be small immediately after emergence from the column of gas, that is, when it is observed within a distance of a centimetre or two from the track of the primary beam, and should increase at a greater distance from it. Such a result is

* Phil. Mag. xxxvii. p. 161 (1919).

† *Loc. cit.*

obviously quite inadmissible, besides being contrary to experience. The fallacy lies in Larmor's assumption that the change of wave-length (Doppler effect) has an effect on the relative phases of the scattered waves, whereas in reality it has none. To make this clear, we may consider two neighbouring molecules A and B. The scattered waves originating from them travel outwards with an identical velocity which is quite unaffected by any movements of these molecules. The phase-difference at any epoch therefore remains unaffected as the waves move out, being exactly the same as when the portions of the wave-train under consideration left the molecules. In other words, the phase-difference at each stage is exactly the same as if the molecules had remained fixed from the instant of emission of the scattered light. The scattering from any appreciable volume of gas would thus remain unaffected if all the molecules were assumed suddenly to be fixed in their instantaneous positions, and the Doppler effect due to their movement exerts no influence whatever on the observed results. Larmor's suggestion, therefore, clearly fails, and we have to fall back upon the view already expressed that the *principle of random phase of the scattered waves rests upon the random character of the distribution of the molecules in space in a gas obeying Boyle's law.*

4. *Application of Boltzmann's Distribution Law.*

It is clear from the preceding discussion that if the distribution of the molecules of a gas or vapour in space is *not* a random arrangement, the intensity of the light scattered would not be given by the Rayleigh law, that is, would cease to be simply proportional to the number of molecules per unit volume. In the usual treatments of the kinetic theory of gases, the molecules are conceived to exert forces on each other, and if the time during which the forces acting on any individual molecule are sensible forms an appreciable fraction of the whole time, the arrangement of the molecules would not be a random one. The influence of the molecules on each other would not then be negligible, and the energy-effects of the individual molecules could not be added up to find the total light scattered in the manner contemplated by the simple theory. It is, however, possible to make a calculation of the altered scattering power of the gas. Let $\phi(r)$ be the law of repulsive force between any two molecules whose centres are at a distance r from each other. By a suitable assumption regarding the nature of $\phi(r)$, it is possible to

include in this function the cohesive or van der Waals's forces which act when the molecules are not in collision with each other, and also the large repulsive forces occurring during actual impact. According to a well-known theorem due to Boltzmann*, the chance that two molecules find themselves at a finite distance r apart is less than the chance that they are at a very great distance apart in the ratio

$$e^{-\frac{1}{RT}\int_r^\infty \phi(r)dr}, \quad \ldots\ldots \quad (4)$$

where $\int_r^\infty \phi(r)dr$ obviously expresses the potential energy of the configuration. The probability of groups of three, four, or more molecules being found at specified distances apart may be similarly expressed in terms of the potential energies of the respective configurations. If we assume that the deviation from Boyle's law is not very large, expression (4) will suffice to enable us to take into account the mutual influence of the molecules in determining their ordering in space. Consider a sphere of radius l drawn round the instantaneous position of a given molecule as centre. If n be the whole (actual) number of molecules in the volume of the gas or vapour, the number to be expected within this sphere of volume $\frac{4}{3}\pi l^3$ is

$$\int_0^l \mathrm{A} \,.\, 4\pi r^2\, dr\, e^{-\frac{1}{RT}\int_r^\infty \phi(r)dr} \qquad (5)$$

where A is a constant to be presently determined. Integrating by parts, (5) reduces to

$$\mathrm{A}\left[\frac{4}{3}\pi r^3 e^{-\frac{1}{RT}\int_r^\infty \phi(r)dr} - \frac{1}{RT}\int_0^l \frac{4}{3}\pi r^3 \phi(r)dr\, e^{-\frac{1}{RT}\int_r^\infty \phi(r)dr}\right]_0^l . \quad (6)$$

To enable this expression to be reduced, we will assume that the force $\phi(r)$ between two molecules vanishes sensibly when $r \gtrless \sigma$, where σ is the range of molecular action. The expression (6) then reduces to

$$\mathrm{A} \,.\, \frac{4}{3}\pi l^3 - \frac{\mathrm{A}}{3RT}\int_0^\sigma 4\pi r^2 r\, \phi(r)\, dr\, e^{-\frac{1}{RT}\int_r^\infty \phi(r)dr}, \quad . \quad (7)$$

provided $l \gtrless \sigma$. When l is very great, the first term in (7) will be very large in comparison with the second, and since (7) must then give the total number of molecules, we find at once $\mathrm{A} = \frac{n}{v}$. We may denote the integral in (7) by C;

* *Vorlesungen über Gastheorie* II. See also Jeans' 'Dynamical Theory of Gases,' 3rd ed. p. 132.

and putting $l=\sigma$, we find that, on the average, the number of molecules which we may expect to find within the sphere of action of the specified molecule is

$$\frac{n}{v}\cdot\frac{4}{3}\pi\sigma^3-\frac{nC}{v.3RT}, \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and is thus smaller than the number corresponding to a random distribution of the molecules by $\frac{nC}{v.3RT}$. (If C be negative, the number will be greater.)

In order to evaluate the intensity of the scattered light, we may now apply the general method developed by the late Lord Rayleigh *. The disturbance due to the scattered waves may be represented by the summation

$$\Sigma\cos(pt+\epsilon_1), \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where ϵ_1 represents the phase of the scattered wave arising from a molecule and is easily expressed in terms of the position of the molecule and the directions of the incident and scattered rays. The *intensity* of the scattered light is obviously represented by

$$\begin{aligned}&[\cos\epsilon_1+\cos\epsilon_2+\cos\epsilon_3+\ldots.]^2\\&+[\sin\epsilon_1+\sin\epsilon_2+\sin\epsilon_3+\ldots.]^2\\&=n+2\Sigma\cos(\epsilon_1-\epsilon_2), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)\end{aligned}$$

where n is the number of molecules and the summation $\Sigma\cos(\epsilon_1-\epsilon_2)$ has to be made for all the $\frac{1}{2}n(n-1)$ pairs of molecules contained in the volume. For a random distribution, $\Sigma\cos(\epsilon_1-\epsilon_2)$ vanishes, as has been shown by Lorentz and by Rayleigh. In the present case, the distribution differs from a random one in that the average number of molecules present within the sphere of action of a molecule is smaller by $\frac{n}{v}\frac{C}{3RT}$. The summation indicated in (10) will not therefore reduce to n simply. Since the radius of action σ of the molecules is much less than the wave-length of the light, the value of $(\epsilon_1-\epsilon_2)$ for the missing molecules may without appreciable error be taken to be zero, and hence, when the summation is carried out for all the molecules in the volume v, (10) will reduce to

$$n\left(1-\frac{n}{v}\cdot\frac{C}{3RT}\right). \quad . \quad . \quad . \quad . \quad (11)$$

* Phil. Mag. xxxvi. pp. 429–449 (1918).

From this it is seen that if C be positive, the intensity of the scattered light is less than that given by the Rayleigh law, while if C be negative, it is *greater*.

In order to interpret the result contained in (11), we notice that, the integral in the second term of (7) which we have denoted by C when multiplied by $\frac{1}{2}\frac{n^2}{v^2}$ represents the *virial function* for the gas or vapour. The virial equation is in fact simply *

$$pv = n\mathrm{RT} + \frac{1}{6}\frac{n^2}{v}\mathrm{C}. \quad . \quad . \quad . \quad . \quad . \quad (12)$$

By differentiating (12), the compressibility β of the gas or vapour may be written as

$$\beta = -\frac{1}{v}\frac{dv}{dp} = \frac{1}{n\frac{\mathrm{RT}}{v}\left(1+\frac{n}{v}\frac{\mathrm{C}}{3\mathrm{RT}}\right)} \quad . \quad . \quad . \quad (13)$$

$$= \frac{v}{n\mathrm{RT}}\left(1-\frac{n}{v}\frac{\mathrm{C}}{3\mathrm{RT}}\right), \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

to the same degree of approximation as used previously. On comparing (14) with (11), it is seen that the intensity of the light scattered per unit of volume, instead of being proportional to $\frac{n}{v}$ as required by the Rayleigh law, is proportional to

$$\frac{n^2}{v^2}\mathrm{RT}\beta, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

and thus varies directly as the absolute temperature, the square of the density of the substance and its compressibility. In the case of a gas obeying Boyle's law, $\beta = \frac{1}{p}$ and $pv = n\mathrm{RT}$, and (15) becomes simply $\frac{n}{v}$ in agreement with the Rayleigh law.

5. *The Theory of Density Fluctuations.*

The result deduced by us in the preceding section from the principles of the kinetic theory for the case of moderately compressed gases agrees with the general formula obtained

* This agrees with Keesom's approximate equation of state, containing only the first two terms in the expansion of the virial function. Proc. Roy. Acad. Sciences, Amsterdam, vol. xv. p. 264.

in an entirely different manner by Einstein * in developing an explanation given by Smoluchowski † of the phenomenon of opalescence exhibited by fluids in the vicinity of the critical state. Einstein's reasoning is of a very general character and makes no use whatever of the molecular hypothesis. It is based on the following train of ideas. If, in the condition of equilibrium, the medium is conceived of as a completely uniform homogeneous system, there can be no scattering of the light-waves passing through it. Actually, however, as Smoluchowski showed from thermodynamical considerations, the density of the substance must vary from point to point, and also fluctuate from instant to instant, the density as measured by our ordinary appliances being merely a statistical average. Hence, in framing the electromagnetic equations, the dielectric constant (which is assumed to vary with the density in the manner contemplated by the Lorentz-Mossotti formula) must be regarded as varying from point to point, and the solution of the equations for wave-propagation contains, besides the regularly transmitted waves, also an opalescence radiation which is a volume-effect and represents the scattered light resulting from the local inequalities of density. Einstein's treatment naturally therefore falls into two parts: firstly, the determination of the magnitude of the fluctuations of the dielectric constant for the elements of volume, secondly, the calculation of the opalescent radiation.

The magnitude of the density-fluctuations is calculated by Einstein in the following manner:—Boltzmann's well-known thermodynamical principle connects the entropy S of a system with the probability W to which the entropy S relates by the equation

$$S = R \log W + \text{constant}, \quad . \quad . \quad . \quad . \quad (16)$$

where R is the gas-constant. Einstein points out that the entropy S of the whole system does not completely define the physical conditions of the small individual parts of the system at any instant, and hence (16) should be understood as referring to an *ensemble* of different possible conditions of the system in each of which its entropy is S. If we consider particular parts of the system and particular instants of time, fluctuations from the ideal thermodynamic equilibrium must appear, the magnitude of which is determined by the corresponding changes of entropy of the parts of the system. For an isothermal compression or rarefaction, the change of

* *Annalen der Physik*, xxxiii. p. 1294 (1910).
† *Loc. cit.* xxv. p. 205 (1908).

entropy is simply the work done divided by the absolute temperature. Boltzmann's theorem may be written in the form

$$W = e^{\frac{S-S_0}{R}}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

where S_0 is the entropy in the state of thermodynamic equilibrium. Taking ν to be the deviation of some observable physical variable, *e. g.* in this case the density, from the value corresponding to thermodynamic equilibrium, Einstein writes (17) in the form

$$W(\nu)d\nu = Ae^{-\frac{1}{2RT}a\nu^2} d\nu, \quad . \quad . \quad . \quad . \quad (18)$$

where $W(\nu)d\nu$ is the probability that ν lies between ν and $\nu + d\nu$, A is a constant, and $\frac{1}{2}a\nu^2$ is the work done in altering ν from 0 to ν. (18) evidently has the same form as Gauss's error-law, and it follows that

$$\overline{\tfrac{1}{2}a\nu^2} = \tfrac{1}{2}RT, \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

where the bar indicates the *mean* value of the quantity under consideration. If we identify ν with $(\Delta\rho)$ the fluctuation of density, its mean square may be evaluated from (19) and written in the form

$$\overline{(\Delta\rho)^2} = \frac{RT\beta\rho_0^2}{\phi}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

where β is the isothermal compressibility, ϕ is the small element of volume under consideration, and ρ_0 is the mean density.

For the deduction of the light-scattering from (21) with the aid of Maxwell's electromagnetic equations, reference should be made to Einstein's original paper. We may follow here an abbreviated treatment which gives an identical result.

At right angles to the incident light the intensity of scattered light is given by the expression *

$$\frac{\pi^2\phi^2(\Delta\epsilon)^2}{2\lambda^4}\frac{1}{r^2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$(\Delta\epsilon)$ being the variation of the dielectric constant.

Now, as the individual local variations of the dielectric constant are irregularly distributed, the phases of the various scattered beams are also quite arbitrary, and hence for calculating the total intensity of scattered light we have

* Rayleigh, Phil. Mag. p. 81 (1881); Sc. Papers, vol. i. p. 526.

merely to sum up the above expression over the total volume v. The expression contains a factor

$$\Sigma(\Delta\epsilon)^2\phi^2,$$

which may be evaluated by use of the Mosotti-Lorentz law

$$\frac{\epsilon-1}{\epsilon+2}=\text{const.}\,\rho.$$

Differentiating, we obtain

$$(\Delta\epsilon)^2=\frac{(\epsilon-1)^2(\epsilon+2)^2}{9}\left(\frac{\Delta\rho}{\rho_0}\right)^2. \quad . \quad . \quad . \quad (22)$$

Substituting in this the value given above for fluctuation of density, we obtain

$$\frac{(\epsilon-1)^2(\epsilon+2)^2}{9}\mathrm{RT}\beta\,\Sigma\,\phi=\mathrm{RT}\beta\frac{(\epsilon-1)^2(\epsilon+2)^2}{9}\,.\,v. \quad (23)$$

Thus the intensity of light scattered by a cubic centimetre of fluid at right angles to the incident rays is

$$\frac{\pi^2}{18}\mathrm{RT}\beta\frac{(\epsilon-1)^2(\epsilon+2)^2}{\lambda^4}=\frac{\pi^2}{18}\mathrm{RT}\beta\frac{(\mu^2-1)^2(\mu^2+2)^2}{\lambda^4}. \quad (24)$$

In the cases of gases and vapours, whether obeying Boyle's law or not, the formula (24) may be appreciably simplified by assuming $(\mu^2+2)=3$, and $(\mu^2-1)^2=4(\mu-1)^2$ approximately, and it may then be written in the form

$$\frac{2\pi^2(\mu-1)^2\mathrm{RT}\beta}{\lambda^4}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

If the gas or vapour obeys Boyle's law, $\beta=\frac{1}{p}$ and $pv=n\mathrm{RT}$, and (25) becomes identical with the Rayleigh law. In other cases, (25) is seen to agree with formula (15) when the omitted multiplying factors are restored.

It may be pointed out that the expression giving the magnitude of the density-fluctuation might have been derived immediately from the principle of equipartition of energy, as is indeed evident from the form of the relation (19). In the case of a gas obeying Boyle's law in which the molecules are distributed at random throughout the space, the mean square of the density-fluctuation may also be derived by direct application of the theory of probabilities, and the intensity of the scattering calculated therefrom. This has been done by Lorentz *, and the result naturally agrees with that obtained by Rayleigh.

* Proc. Roy. Soc. Amsterdam, xiii. p. 92 (1911).

6. *Experimental Tests of the Einstein-Smoluchowski Formula.*

The expression given by Einstein for the light-scattering in a direction transverse to the primary beam, viz. :

$$\frac{\pi^2}{18}\,\frac{R_1 T\beta}{N_1}\,\frac{(\mu^2-1)^2(\mu^2+2)^2}{\lambda^4},$$

where R_1 and N_1 represent the gas-constant and the Avogadro-number respectively for a a *gram-molecule*, was originally developed by him to explain the opalescence exhibited by fluids in the vicinity of the critical state. It should, however, possess a far wider and *general* application, and indeed be regarded as superseding the Rayleigh law of scattering, which should only be valid in the special case of gases accurately obeying Boyle's law. It is thus of great importance to test the validity of the Einstein-Smoluchowski formula over a very wide range of cases. So far as the authors are aware, the only experimental tests that have so far been made of it for the case of a single substance in the gaseous state are those of Kammerlingh Onnes and Keesom * on the opalescence of ethylene vapour, but the work of these investigators was confined to a range of only 2·5 degrees of temperature *above* the critical temperature of this substance. A far more comprehensive and general test of the formula for several substances over the widest possible range of temperatures and pressures is obviously desirable, and researches with this object have been undertaken in the authors' laboratory. The first substance chosen was ether. This substance has a high refractivity and therefore a large scattering power in the state of vapour, and its critical temperature and pressure are moderate, and it also possesses a high degree of chemical stability under the action of heat and light. It is therefore very well suited for quantitative work. The detailed account of the determinations carried out with it by one of us (K. R. Ramanathan) will be published in a separate paper, and it will suffice here to indicate the general scope of the work and the results obtained. The light-scattering power of ether has been determined separately for the substance in the saturated vapour and in the liquid phases for temperatures from 30° C. to the critical temperature 194° C., and for the gaseous phase from 194° C. to 217° C. The vapour and gaseous phases deviate very largely from Boyle's law, the compressibility being larger than the reciprocal of the pressure, especially at the higher temperatures, and the

* *Loc. cit.* (1908).

measurements throughout the whole range show that the *Rayleigh law of scattering completely breaks down* and strikingly confirm the correctness of the Einstein-Smoluchowski formula. The scattering power of the vapour when it is dense is in fact several times larger than that given by the Rayleigh law, and this feature is more and more pronounced as the critical temperature is approached from either side. The Einstein-Smoluchowski formula also shows itself to be equally applicable to the case of liquids over the whole range of temperature tried.

7. *Polarization of the Scattered Light.*

It should be noted that, according to Einstein's investigation, the light scattered in a direction transverse to the primary beam should be completely polarized. Actually, however, this is not the case. The imperfectness of the polarization of the light scattered by gases was first discovered by Strutt (the present Lord Rayleigh), and measurements of the magnitude of the effect have been made by a photographic method by him * and by Cabannes † and also by Gans ‡. The imperfect polarization can be detected visually even in the case of dust-free air at atmospheric pressure §, and with the gases at high pressure, the increased intensity enables *visual measurements* to be carried out. In the case of ether vapour, the effect is very feeble, the polarization in the transversely scattered light being nearly complete (about 98·5 per cent.), but the great intensity of the scattered light enables *visual* measurements to be carried out, and it is found that with increasing density of the vapour, the percentage of polarization does not appreciably change. In the case of the liquid, specially interesting effects are observed which will be dealt with in a separate paper.

Cabannes ‖ has shown that owing to the imperfect polarization, the intensity of the transversely scattered light is increased and is greater than that given by the Rayleigh law in the ratio $\frac{6(1+\rho)}{6-7\rho}$, where ρ is the ratio of the weaker to the stronger component of polarization. It is found that the Einstein-Smoluchowski formula should be modified by a similar correcting factor in order to give results in agreement with experiment. The correction becomes very important when ρ is large.

* Proc. Roy. Soc. xciv. p. 453 (1918).
† *Ann. de Physique*, xv. pp. 1–150.
‡ *Ann. der Physik*, lxv. p. 97 (1921).
§ 'Nature,' Jan. 19, 1922.
‖ *Loc. cit.*

8. *Relation of Molecular Scattering to Critical Opalescence.*

As we have already seen, the Einstein-Smoluchowski formula shows that there is a perfect continuity between the comparatively feeble light-scattering shown by gases and vapours under ordinary conditions and the extremely large scattering or opalescence which develops as the critical state is approached. At the critical point itself, the compressibility of the substance is infinite, and it follows that the Einstein-Smoluchowski formula gives an infinite value for the scattering power. This is obviously inadmissible, and Einstein * himself has pointed out that for a *very minute* region at and round the critical point, the neglect of second-order terms in the expression for the work done in altering the density is not permissible and the formula requires modification. This point has, however, not much importance for our present purpose, as the range of temperature over which the neglect of the second-order terms is not permissible is exceedingly small. It may be mentioned that the matter has been further discussed by Ornstein and Zernike †, who have proposed an amended formula applicable in the immediate neighbourhood of the critical point which leads to a finite value for the scattering at this point. The bearing of Ornstein and Zernike's results on the phenomena observed with ether will be dealt with separately.

9. *The Case of Carbon Dioxide and the permanent gases.*

The experimental confirmation of the Einstein-Smoluchowski formula for the case of ether vapour, and also in the case of various ordinary liquids, shows that its theoretical basis is thoroughly firm and that the formula may be justly expected to apply equally well in the case of other gases and vapours. It is therefore very important that the case of carbon dioxide and the permanent gases, *e. g.* oxygen, nitrogen, argon, &c., should be thoroughly investigated. The scattering power of saturated carbon dioxide vapour at 21° C. (that is, ten degrees below the critical temperature) has been determined by the present Lord Rayleigh, and found to be 102 times that of the gas at atmospheric pressure. The compressibility of carbon dioxide at this temperature is very great, and the Einstein-Smoluchowski formula shows that the scattering power of saturated carbon dioxide at 21° C. should have been about 855 times that of the gas at atmospheric pressure. The observed result thus apparently supports the Rayleigh law of scattering (the density of carbon dioxide at this temperature being about

* *Ann. der Physik*, xxxiii. p. 1275 (1910).
† Proc. Amsterdam, xvii. p. 793 (1914).

110 times the density of atmospheric pressures), and not the Einstein-Smoluchowski formula. The experimental result is however open to question, as Rayleigh mentions that his observation tube had a leak, and the density of the gas was therefore probably much less than that corresponding to the saturation pressure. Some observations made in a Cailletet tube containing CO_2 liquid and vapour by the authors show that both carbon dioxide liquid and vapour scatter light very strongly at and for a few degrees below the critical temperature, but the scattering power falls off very quickly with decreasing temperature. It is hoped to carry out a series of measurements at different temperatures with improved apparatus, and to obtain data in order decisively to settle the question whether the Einstein-Smoluchowski formula does really break down for carbon dioxide. Probably standing in very close relation to this is the fact that has been observed by Kammerlingh Onnes and his co-workers at the Leiden Laboratory, that pure oxygen, nitrogen *, and argon do not show the phenomenon of critical opalescence. It is obviously of the greatest importance to investigate whether in these cases the Einstein-Smoluchowski formula is applicable or not.

Till further data are available, it is probably not safe to venture an opinion, but it seems clear that the applicability of the thermodynamic reasoning of Einstein and Smoluchowski stands on an unchallengeable basis at least at ordinary temperatures and so far as gases and liquids are concerned. It will be noticed that the formula was derived on the basis of the classical theory of light in which it is assumed to consist of some form of continuous wave-propagation. In view of recent work in various modern fields of physics, and the known failure of the classical theory in explaining the facts regarding the emission and absorption of light, the question arises whether we are justified in assuming that the classical wave theory is necessarily capable of giving a strict quantitative explanation of the facts regarding the molecular scattering of light? Is it not possible that in the case of substances whose molecules have a relatively small light-scattering power, the infinite sub-divisibility of the energy of the incident waves which the classical theory assumes might break down? Then again is it not possible that the statistical-mechanical considerations on which the validity of Boltzmann's principle rests might require modification in the sense of the quantum theory, particularly in dealing with fluids at low temperatures? The answer to these questions can only be given when a more thorough experimental investigation of the facts of molecular

* Proc. Amsterdam Academy, xviii. p. 950 (1915).

scattering in dense vapours has been carried out. Such investigation has been undertaken by the authors, and it is hoped that before long the necessary data will be available.

10. *Summary.*

The paper considers the problem of the molecular scattering of light in dense vapours and gases *not* obeying Boyle's law. The following are the principal results :—

(1) It is shown by a discussion that the Rayleigh law of scattering, which is based on the assumption of a random distribution of the molecules in space, should not be applicable in these cases.

(2) Assuming the non-random distribution of the molecules in space to be given by Boltzmann's theorem, a calculation is made of the scattering power of the medium. The result obtained is interpreted with the aid of the virial equation, and it is shown that the scattering power per unit volume is proportional to the absolute temperature, to the square of the density of the substance, and to its compressibility. If the gas obeys Boyle's law, the expression reduces to the Rayleigh law.

(3) The result thus deduced directly from the principles of the kinetic theory agrees with the general formula derived from the thermodynamical theory of density fluctuations, developed by Einstein and Smoluchowski, of which a brief account is given.

(4) Experiments carried out with ether vapour and liquid over a large range of temperature both below and above the critical point completely confirm the Einstein-Smoluchowski formula for this substance.

(5) The corrections of the formula necessary in view of the imperfectness of the polarization of the transversely scattered light, and also in the immediate neighbourhood of the critical point when the compressibility becomes excessively great, are indicated.

(6) The cases of carbon dioxide and of the permanent gases are referred to and the possible significance of the results obtained in their cases is discussed.

Calcutta, India.
April 22nd, 1922.

Note added in proof (*6th August*) : Since the paper was sent in, experiments on the light-scattering in the vapours of benzene and pentane at different temperatures and also in *carbon dioxide* at high pressure contained in sealed bulbs have been carried out, and these definitely confirm the Einstein-Smoluchowski formula and show that the Rayleigh law of scattering is not valid except in gases obeying Boyle's law.

XVII. *The Molecular Scattering of Light in Liquid Mixtures.*

By C. V. Raman, *M.A.*, *Hon.D.Sc.*, *Palit Professor of Physics in the Calcutta University, and* K. R. Ramanathan, *M.A.*, *University of Madras Research Scholar* *.

1. *Introduction.*

As is well known, there are many substances, *e. g.* phenol and water, which in the liquid state dissolve each other completely and form a single phase above a certain temperature, but below it are only partially soluble and divide into two coexistent phases. Such mixtures exhibit a marked opalescence or turbidity at temperatures slightly higher than that at which they separate into two layers. Smoluchowski † put forward a thermodynamic explanation of this phenomenon as due to the spontaneous local fluctuations of concentration which occur in the mixture and cause optical inhomogeneity. The problem was further handled by Einstein ‡, who made certain simplifying assumptions, namely, that the liquids are incompressible, that their specific volumes are negligibly small in comparison with those of the saturated vapours emitted by them, and that the latter can be treated as ideal gases, and on this basis derived a formula for the opalescence of the mixture in terms of experimentally determinable magnitudes, that is, the variation of its refractive index and of the partial vapour-pressures of its components with alteration of concentration. The simplifications referred to, however, considerably restrict the validity of the investigation which, in fact, can be regarded as strictly applicable only over a small range of temperature above that at which the mixture separates into two phases. For such a restricted range, the correctness of Einstein's formula has been experimentally established by the investigations of Fürth § and of Zernike ‖. Actually, however, by using carefully purified liquids freed from dust by repeated distillation *in vacuo*, the opalescence in mixtures may be studied over any desired range of temperature and not merely in the immediate vicinity of the critical solution point, and very remarkable and interesting changes in the intensity of the scattered

* Communicated by the Authors.
† *Annalen der Physik*, xxv. p. 219 (1908).
‡ *Annalen der Physik*, xxxiii. p. 1295 (1910).
§ *Wiener Sitzungsberichte*, p. 577, 1915.
‖ Thèse, Amsterdam, 1915.

Phil. Mag. 45, 213–224, 1923.

light and the state of its polarization are observed. These phenomena are also noticeable in mixtures of liquids which are completely soluble in each other at the ordinary temperature. It is found that Einstein's approximate investigation is not adequate to explain the observed facts in these cases and that a stricter investigation is called for. It is proposed in this paper to show how by a modification of the procedure adopted by Einstein, a *perfectly rigorous* expression for the light-scattering can be derived in terms of experimentally determinable quantities. A comparison is also made between the results of the modified theory and those observed in experiment. Specially noteworthy are the effects arising from *molecular anisotropy* which, of course, are not contemplated at all in Einstein's theory. These are discussed in detail in the course of the paper.

2. *Thermodynamical Theory : Application of Boltzmann's Principle.*

In order to deal with the problem under consideration, Einstein assumed that the refractive index of the mixture is a function of a single variable k which expresses the concentration of the mixture, that is the ratio of the mass of the second component present to that of the first component. This is not, however, correct. We have in reality to deal with *two* independent variables, namely, the densities of both components, and the local fluctuations of refractive index are determined by variations of both of these quantities. One way of determining the accidental deviations of density in a mixture is by applying the principles of statistical mechanics. This has been attempted by Ornstein*. In order, however, to express the results in terms of physically measurable quantities, it is simpler to use a purely thermodynamical treatment based upon Boltzmann's well-known relation between entropy and probability. In order to make use of this principle, we have to find the change of entropy resulting from small increases Δm_1 and Δm_2 in the masses, m_1 and m_2 of the components actually present in unit volume of the mixture. The probability of such deviations occurring spontaneously and their mean value may then be evaluated. In order to find the change of entropy involved we have to imagine the masses Δm_1 and Δm_2 introduced into unit volume of the mixture isothermally and by a reversible process. The following thermodynamical operation, which is a modification of that used by Einstein, enables this to be done.

* Proc. Roy. Soc. Amsterdam, xv. p. 54 (1912).

Consider unit volume of the mixture enclosed in a cylinder fitted with a frictionless piston by which the hydrostatic pressure can be varied. The base of the cylinder has two openings, which may be either closed at will or fitted with membranes permeable respectively to the vapour of the first and second components only. A second and much larger reservoir similarly fitted with a piston and semi-permeable openings is assumed to be filled with the liquid mixture, this being maintained at the same temperature and at a hydrostatic pressure equal to the total vapour pressure ϕ of the mixture. The following isothermal operations may then be carried out.

Stage 1.

By means of auxiliary pumps applied to the semi-permeable openings, small masses (Δm_1) and (Δm_2) of the two components may be removed in the state of vapour from the reservoir, the volume of which is assumed to be so great that no appreciable alteration in the composition of its contents occurs in consequence of this removal.

If p_1 and p_2 be respectively the partial pressures of the vapours and v_1 and v_2 their specific volumes, the work done in the process is

$$-p_1v_1\Delta m_1-p_2v_2\Delta m_2+[s_1\Delta m_1+s_2\Delta m_2]\phi, \quad . \quad . \quad (1)$$

where s_1 and s_2 represent respectively the shrinkages of the volume of the mixture by removal of unit masses of the two components.

Stage 2.

Taking the masses (Δm_1) and (Δm_2) of the vapours thus separated, force simultaneously a mass (Δm_1) of the first component and a mass $(k\Delta m_1)$ of the second component into the cylinder the contents of which are maintained at a constant hydrostatic pressure ϕ, k being the fraction m_2/m_1. It is clear that in this operation the composition of the mixture, and therefore also its vapour-pressure, remain unaltered. The work done in this process is therefore

$$p_1v_1\Delta m_1+p_2v_2k\Delta m_1-[s_1\Delta m_1+s_2k\Delta m_1]\phi. \quad . \quad . \quad (2)$$

Stage 3.

Force the remaining portion $(\Delta m_2-k\Delta m_1)$ of the second component into the cylinder, the hydrostatic pressure in it

being maintained at the equilibrium value of its total vapour-pressure at each instant. The work done in this process is

$$v_2(\Delta m_2 - k\Delta m_1)(p_2 + \tfrac{1}{2}\Delta p_2) - s_2(\Delta m_2 - k\Delta m_1)(\phi + \tfrac{1}{2}\Delta\phi), \quad . \quad (3)$$

where (Δp_2) and $(\Delta\phi)$ represent respectively the changes of the partial vapour-pressure and the total vapour-pressure resulting from the operation.

Stage 4.

The volume of the mixture in the smaller cylinder is now greater than at first by $(s_1\Delta m_1 + s_2\Delta m_2)$. The semi-permeable openings are now closed, and the piston enclosing the contents forced in by increasing the hydrostatic pressure till the original volume is restored. The work done in this process is

$$\tfrac{1}{2}\beta(\Delta p)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where β is the compressibility, of the mixture and (Δp) is the increase of hydrostatic pressure in the process.

Adding up (1), (2), (3), and (4) we find the total work done is

$$\tfrac{1}{2}(v_2\Delta p_2 - s_2\Delta\phi)(\Delta m_2 - k\Delta m_1) + \tfrac{1}{2}\beta(\Delta p)^2. \quad . \quad . \quad (5)$$

The quantity k is a measure of the concentration of the mixture. If it be altered to $k+\Delta k$ as the result of the operations set out above, it is easily seen that $m_1\Delta k = (\Delta m_2 - k\Delta m_1)$.

Hence (5) may be written in the form

$$\tfrac{1}{2}m_1\left(v_2\frac{\partial p_2}{\partial k} - s_2\frac{\partial\phi}{\partial k}\right)(\Delta k)^2 + \tfrac{1}{2}\beta(\Delta p)^2,$$

or, for brevity,

$$\tfrac{1}{2}\alpha(\Delta k)^2 + \tfrac{1}{2}\beta(\Delta p)^2. \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The next step is to find the mean value of $(\Delta k)^2$ and $(\Delta p)^2$ in the deviations which occur spontaneously in a volume-element dv of the mixture. We may for this purpose use Boltzmann's principle in the form in which it has been expressed by Einstein,

$$dW = Ce^{-\frac{NE}{RT}}d\lambda_1 d\lambda_2 \ldots . d\lambda_n, \quad . \quad . \quad . \quad (7)$$

where $\lambda_1, \lambda_2 \ldots . \lambda_n$ are suitably chosen variables which determine the observable condition of the system and dW is the probability that the magnitudes λ_1, λ_2, etc., lie between λ_1 and $\lambda_1 + d\lambda_1$, λ_2 and $\lambda_2 + d\lambda_2$, etc., R, T, and N have the same significance as in kinetic theory. C is a constant and E is the work necessary to bring the system into the state

under consideration from that of thermodynamical equilibrium. If $\lambda_1, \lambda_2 \ldots$. are assumed to be zero in the state of equilibrium and E can be expressed in the form

$$E = \tfrac{1}{2}a_1\lambda_1^2 + \tfrac{1}{2}a_2\lambda_2^2 + \ldots. + \tfrac{1}{2}a_n\lambda_n^2, \quad . \quad . \quad . \quad (8)$$

then (7) assumes the familiar form of the Gaussian error-law and it may easily be shown by integration that

$$\left.\begin{aligned} \overline{\lambda_1}^2 = RT/Na_1,\ \overline{\lambda_2}^2 = RT/Na_2, \text{ etc.,} \\ \overline{\lambda_1\lambda_2} = \overline{\lambda_2\lambda_3} \ldots. = 0, \end{aligned}\right\}, \quad . \quad . \quad (9)$$

where the bars indicate the *mean value* of the quantities written under them.

Comparing (6) and (8), we find from (9) that for an elementary volume dv of the mixture

$$\left.\begin{aligned} (\overline{\Delta k})^2 &= \frac{RT}{N}\frac{1}{\overline{\alpha dv}}, \\ (\overline{\Delta p})^2 &= \frac{RT}{N}\frac{1}{\overline{\beta dv}}, \\ \text{and } \overline{\Delta k}\,\overline{\Delta p} &= 0. \end{aligned}\right\} \ldots\ldots\ldots (10)$$

Writing $\epsilon = \mu^2$ where μ is the refractive index of the mixture,

$$\Delta\epsilon = \frac{\partial\epsilon}{\partial k}\cdot\Delta k + \frac{\partial\epsilon}{\partial p}\Delta p,$$

and from (10), it follows at once that

$$(\overline{\Delta\epsilon})^2 = \frac{RT}{Ndv}\left[\left(\frac{\partial\epsilon}{\partial k}\right)^2\Big/\alpha + \left(\frac{\partial\epsilon}{\partial p}\right)^2\Big/\beta\right]. \quad . \quad . \quad (11)$$

3. *Intensity of the Scattered Light: Comparison with Einstein's formula.*

From (11), the intensity of the opalescence radiation can be easily calculated. Using a relation given by the late Lord Rayleigh *, we find that in a direction at right angles to the incident beam (assumed to be unpolarized and of unit intensity), the intensity of the scattered light is

$$I = \Sigma\frac{\pi^2(dv)^2(\overline{\Delta\epsilon})^2}{2\lambda^4}\Big/r^2,$$

where λ is the wave-length and r is the distance of the volume-element from the point of observation. Substituting

* Scientific Papers, vol. i. p. 526.

for $(\Delta\epsilon)^2$ from (11), and integrating over the whole volume of the fluid, say Ψ,

$$I=\frac{\Psi}{r^2}\cdot\frac{\pi^2 RT}{2N\lambda^4}\left[\left(\frac{\partial\epsilon}{\partial k}\right)^2\Big/ m_1\left(v_2\frac{\partial p_2}{\partial k}-s_2\frac{\partial\phi}{\partial k}\right)+\beta\rho^2\left(\frac{\partial\epsilon}{\partial\rho}\right)^2\right], \quad . \quad . \quad (12)$$

where ρ is the density of the mixture.

The principal difference between Einstein's expression for the light-scattering in liquid mixtures and that given here is that the former does not include the term proportional to the compressibility of the mixture which appears in (12). This term expresses the light-scattering due to the local thermal *fluctuations of density* in the mixture considered as a single substance. Using Lorentz's relation $(\epsilon-1)/(\epsilon+2)=\text{const.}\rho$, the second term in (12) may be developed and written in the form

$$\frac{\pi^2 RT\beta}{18N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2\frac{\Psi}{r^2}. \quad . \quad . \quad . \quad (13)$$

The first term in (12) which represents the light-scattering due to the local *fluctuations of concentration* in the mixture may be simplified if we neglect $s_2\dfrac{\partial\phi}{\partial k}$ in comparison with $v_2\dfrac{\partial p_2}{\partial k}$ and assume, further, that the saturated vapour obeys the gas laws, in which case it may be written as

$$\frac{M_2}{2N\lambda^4}\cdot\frac{\frac{1}{m_1}(\partial\epsilon/\partial k)^2}{\partial\log p_2/\partial k}\cdot\frac{\Psi}{r^2}, \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where M_2 is the molecular weight of the second component in the gaseous phase. (14) is Einstein's approximate result. The simplifications here made are only permissible when the vapour-pressure is not large.

The relative importance of the two effects, viz. the light-scattering due to fluctuations of density and concentration respectively, which contribute to its total observed intensity depends on the circumstances of the particular case. The first effect depends on the refractive index and compressibility of the mixture, and second on the variations of refractive index and of the partial vapour-pressures produced by a change in the composition of the mixture. In the immediate neighbourhood of the critical solution temperature,

the partial vapour-pressures alter very little with the composition of the mixture, and the concentration-scattering becomes very great. On the other hand, at temperatures far removed from the critical solution point or in the cases in which the components are ordinarily completely miscible, the partial vapour-pressures change rapidly with concentration, the concentration scattering becomes less, and if the refractive indices of the components do not differ much, it may even become unimportant in comparison with the density scattering. The relative proportion of the two components in the mixture is also of importance. It is evident that when either of the components forms a vanishingly small proportion of the mixture, the concentration-scattering would disappear and the observed opalescence would be due entirely to the density-scattering in the remaining component. The composition of the liquid would also influence the density-scattering, since the refractive index and compressibility of the mixture are both functions of it.

4. *Effect of Molecular Anisotropy.*

The theory so far discussed rests on a purely thermodynamical basis and leads to the result that the light scattered in a direction transverse to the primary beam should be completely polarized. If we had proceeded on the basis of a molecular theory we should have obtained a precisely identical result, provided the molecules could be treated as isotropic or spherical scattering particles exerting forces on each other. Actually, however, this is far from being the case. Even in the case of gases, the transversely scattered light is known to be imperfectly polarized, and in liquids at ordinary temperatures this imperfectness of polarization of the scattered light is found to be much more strikingly evident. Taking this into account, we may, in considering the case of liquid mixtures, divide the total observed light-scattering in a direction transverse to the primary beam into three parts, which are assumed to be superposed on each other. A part Ω_1 arises from density fluctuations. A part Ω_2 arises from the concentration fluctuations. Both of these consist of polarized light, and their magnitudes are given by the thermodynamic theory already considered. Another part arises from the varying orientations of the anisotropic molecules, and this consists in great measure of unpolarized light. Denoting by r the ratio of intensity of the weak to the strong component of

polarization in the transversely scattered light, we may write

$$r = \frac{2\Omega_4}{\Omega_1 + \Omega_2 + \Omega_3 + 2\Omega_4}, \quad . \quad . \quad . \quad . \quad (15)$$

where $\Omega_3 + 4\Omega_4$ is the total intensity of the orientation-scattering of which a part Ω_3 consists of plane polarized light and the remaining portion, $4\Omega_4$, consists of unpolarized light, and is therefore equally divided between the two perpendicular directions of vibration. For all practical purposes Ω_3* is negligible, and it remains to determine the magnitude of Ω_4.

If we assume that the molecules in a liquid have their *orientations* entirely at random (though their *positions* are *not*), it is readily seen that the unpolarized part of the orientation-scattering would be simply proportional to the number of molecules n_1 and n_2 of each kind present in unit volume, and we may write

$$\Omega_4 = n_1\chi_1 + n_2\chi_2, \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where χ_1, χ_2 are constants characteristic of each kind of molecule. The magnitude of χ_1 and χ_2 may be determined from (15) and (16) when the values of r corresponding to the case in which the liquid contains only one component or the other are known, and the values of r and Ω_4 for any given composition of the mixture may then readily be calculated. The assumption that the orientation-scattering is simply proportional to the number of molecules per unit of volume is shown to be justified by the fact that in a number of cases it enables the value of r to be successfully predicted for a single substance in the state of liquid when the corresponding value of r for the same substance in the state of vapour is known.

It is evident from (15) that when Ω_1 or Ω_2 is very large, r will be very small. In other words, when either the density scattering or the concentration scattering is very large, the transversely scattered light is almost completely polarized. The latter condition arises when the observations are made in the immediate vicinity of the critical solution temperature. The former condition arises at the plait-point temperature of the mixture, *i. e.* at a temperature which

* In the case of gases obeying Boyle's law, only 1/13 of the orientation-scattering consists of polarized light, as has been shown by Born. In the case of liquids under ordinary conditions, it is probably much smaller on account of the partial correlation of phase of the effects of contiguous molecules.

corresponds to the ordinary critical state for a simple fluid. In either of these cases, the orientation-scattering is a negligible part of the whole observed scattering.

5. *Comparison of Theory and Experiment.*

The theoretical results deduced above agree in their general features with experiment. The scattering of light by mixtures of phenol and water of varying concentrations has been studied in the authors' laboratory by Mr. V. S. Tamma for a range of 30° C. above its critical solution temperature (68° C.). The scattering is exceedingly large in the immediate neighbourhood of the critical solution point, and as the temperature is raised its intensity diminishes, but over the whole range the scattering remains much higher than that of the pure liquids taken together or separately. As is indicated by theory, the polarization of the light scattered in the mixture is far more complete than in pure phenol, which shows a large admixture of unpolarized light. Very near the critical solution temperature, the polarization is practically complete. But as the temperature is raised, it becomes less and less perfect.

Experiments have also been made on mixtures of ethyl alcohol and water. As the percentage of alcohol is increased, the scattering increases to a maximum, then comes down to a minimum and again increases. The extra scattering is largest for a mixture containing about 20 per cent. of alcohol. The case of this mixture is particularly complicated, inasmuch as both its compressibility and refractivity are anomalous. At 20° C., the compressibility is a minimum when the percentage by weight of alcohol is nearly 20. The refractivity of the mixture increases as the alcohol-content is increased, and reaches a maximum when there is about 80 per cent. by weight of alcohol, after which it again diminishes.

The following table gives the density-scattering calculated for different compositions in terms of that of water as a unit.

Percentage of alcohol by weight.	Compressibility at $20° \times 10^6$.	Refractive index at 20° C.	Density scattering.
0	49	1·3375	1·00
10	42	1·3436	0·94
20	40	1·3500	0·94
40	47	1·3600	1·20
60	62·5	1·3670	1·68
80	81	1·3693	2·19
100	100	1·3674	2·72

To calculate the concentration-scattering, we require to know the partial vapour-pressures of the components, and curiously enough, the necessary data do not seem to exist for alcohol-water mixtures. Anyhow, the concentration-scattering would vanish at about 80 per cent. by weight of alcohol, since at that point there is no change of refractivity with concentration, and would be very small over the range 60 to 100 per cent. Since the refractivity of alcohol is not very different from that of water, the effect would not be large at any stage. This agrees with the observed facts.

Measurements of the intensity and polarization of the scattered light in binary mixtures of carbon disulphide and ether, and of benzene and normal hexane have been published by W. H. Martin *. By the use of relation (15), we can calculate the orientation-scattering. Partial vapour-pressure data for the first mixture are available †, and from (14) the concentration-scattering can be calculated. But owing to lack of compressibility data, we cannot calculate the density-scattering. Since, however, this forms only a small fraction of the total scattering in the present case, an error in its estimate would not be of much consequence.

In the attached graph are shown, A the concentration-scattering, B the unpolarized scattering, and C the sum of these two for different concentrations. The values of the total experimental scattering are also plotted in curve D. It will be seen that the curve of orientation-scattering is nearly a straight line, showing, in agreement with (16), that it is proportional to the number of the two kinds of molecules per unit volume. The concentration-scattering was calculated by using (14).

Now

$$\frac{\partial \log p_2}{\partial k} = \frac{1}{p_2}\frac{\partial p_2}{\partial k} = -\frac{x^2}{p_2}\frac{\partial p_2}{\partial x},$$

where x is the mass of the first component (in this case CS_2) in unit mass of the mixture. The values of $\frac{\partial p_2}{\partial x}$ were got from the partial vapour-pressure curve of ether. $\frac{\partial \epsilon}{\partial x}$ was calculated from the formula for the refractive index of mixtures

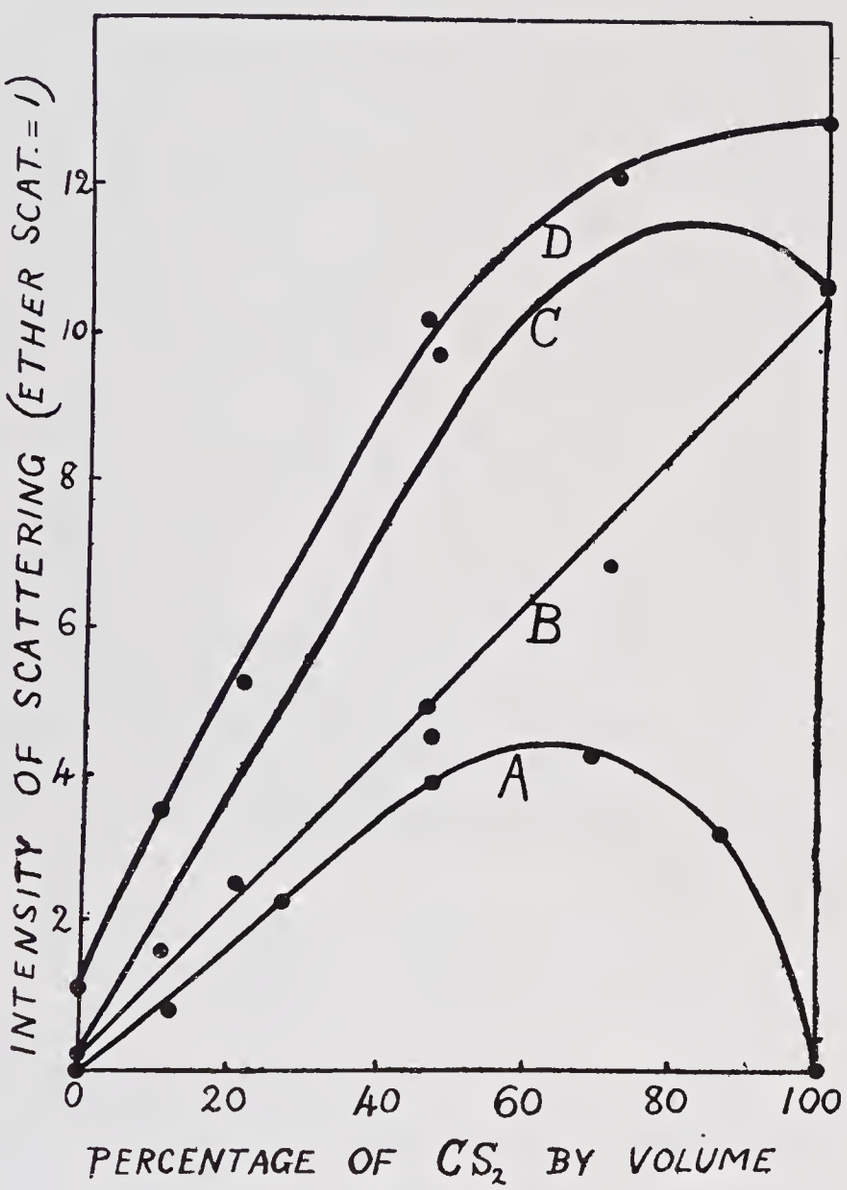
$$\frac{\epsilon-1}{(\epsilon+2)\rho} = \frac{\epsilon_1-1}{(\epsilon_1+2)\rho_1}x + \frac{\epsilon_2-1}{(\epsilon_2+2)\rho_2}(1-x),$$

* Journal of Physical Chemistry, Jan. 1922.

† Guglielmo, *Acc. dei Lincei* (5) 1, i. pp. 242 & 294 (1892).

where e_1, ρ_1, and e_2, ρ_2 refer to the two components of the mixture.

It will be noticed that the curve C closely follows the experimental intensity-curve. The difference, no doubt, represents the density-scattering, which, however, cannot be calculated theoretically (except separately for the two pure liquids) as the compressibility of the mixture is not known.



For pure ether and pure CS_2 the density-scatterings are 0·85 and 2·80, so that if these are added to the orientation-scatterings, the total scattering fits into Martin's experimental curves. To make an adequate test of the theory, we require to know both the compressibilities and the partial vapour-pressures of pairs of liquids. Data regarding partial

vapour-pressures are available for a number of pairs of liquids, and the measurement of compressibilities of mixtures is being undertaken in this laboratory in order to make a complete test of the theory of light-scattering in mixtures.

Summary and Conclusion.

In this paper, the approximate investigation of the scattering of light in liquid mixtures given by Einstein is revised and a perfectly rigorous formula is developed, in which account is taken of the compressibility of the mixture. It is shown that the thermodynamical investigation leads to the result that the light-scattering arises in two distinct ways : (1) due to spontaneous local fluctuations in the composition of the mixture, and (2) due to local fluctuations of its density. Einstein's approximate investigation ignores the second effect, which becomes very important when the observations are made at temperatures not close to the critical solution point or in the case of liquids which are completely miscible at ordinary temperatures.

(*a*) The scattering power is expressed in terms of the compressibility of the mixture, the variations of its refractive index, and the partial vapour-pressures of its constituents with the composition.

(*b*) A discussion is given of the effects of molecular anisotropy which gives rise to an additional "orientation-scattering." It is shown that the polarization of the transversely scattered light is imperfect as the result of molecular anisotropy, but it is considerably less so in the mixture than in the pure liquids, and, further, it becomes more and more perfect as the critical solution temperature is approached.

(*c*) A comparison of the results with the available experimental data shows a general agreement.

(*d*) Very similar methods may also be applied in the case of solutions of solids in liquids, and in the case of ternary mixtures.

Calcutta,
27th July, 1922.

THE MOLECULAR SCATTERING OF LIGHT IN BENZENE, VAPOR AND LIQUID

By K. R. Ramanathan

Abstract

Scattering of sunlight by benzene, vapor and liquid, from 35° to 283° C.— The intensity of the light scattered at right angles was determined relative to that scattered by liquid ether at 35° C, by photometric comparison with the aid of reflecting prisms and a sectored disc. The relative intensity increased with the temperature at an accelerated rate; for the liquid, from 3.2 at 35° to 102 at 283° and, for the saturated vapor, from 0.95 at 182° to 11.9 at 267°. The scattered light is not completely polarized. The *imperfection of polarization* was measured by use of a double-image prism and a nicol. The ratio of the weaker to the stronger component, r, was found to decrease from 7.2 to 0.9 per cent for the vapor and from 43 to 2.8 per cent for the liquid as the temperature was raised from 35° to 280°. *Comparison with theories.* This imperfection has been attributed to the anisotropy of the molecules by Rayleigh, Born and others. The theory as extended by Raman to the general case of fluids leads to the relation $Sr/\rho(1 + r) = \text{const.}$, where S is the intensity and ρ the density. This is found to agree satisfactorily with the observations for both vapor and liquid. Since for the vapor, the intensity S increases with the temperature much more rapidly than the density, the Rayleigh law is not valid. The Einstein-Smoluchowski formula shows much better agreement, although, when calculated values of the refractive index and compressibility are inserted, it gives for the scattering in the vapor values which are 20 per cent or more too high.

Formula for isothermal compressibility of a saturated vapor is derived from Dietrici's equation of state. It is found to give the observed values for ether, isopentane and CO_2 in the temperature range 0.8 to 0.96 T_c if an arbitrary numerical factor 1.25 is used. Introducing this gives, for this range $(dp/d\rho)_t = 2.5p(\rho_c - \rho)^2/(2\rho_c^2\rho - \rho^2\rho_c)$.

1. Introduction.

In his recent experiments on the molecular scattering of light in gases and vapors[1] Lord Rayleigh noticed the interesting fact that the light scattered in a direction perpendicular to the incident beam was not perfectly polarized. A similar effect has been observed but in a much more marked degree by W. H. Martin[2] in the light scattered by dust-free liquids. When we compare a liquid like ether and its vapor at the ordinary temperature in this respect, we find a large difference. Ether vapor at the ordinary temperature shows an imperfection of 1.7 per cent,

[1] Proc. Roy. Soc. A., Vol. 94, p. 453, 1918.

[2] Martin, Journal of Physical Chemistry, Vol. 24, 1920, p. 478, and Jan., 1922.

Phys. Rev. 21, 564–572, 1923.

while liquid ether shows 8 per cent. The imperfection of polarization in gases has been explained [1, 2] on the assumption of anisotropy of the molecules; the imperfection in liquids is no doubt to be attributed to the same cause. The general theory of light-scattering in liquids has been discussed by Prof. C. V. Raman,[3] who has also put forward an explanation[4] of the increased imperfection of polarization of the scattered light in this case and suggested a quantitative connection between the intensity of the transversely scattered light, its state of polarization and the density of the fluid. A brief account of this theory is given in the course of the paper. The experiments described here were undertaken with a view to securing data regarding the intensity and polarization of the transversely scattered light both in the liquid phase and the saturated vapor phase of a suitable substance over a large range of temperatures. Benzene was chosen owing to the large value of its imperfection of polarization at ordinary temperatures. The result of the experiments has been to confirm the general validity of the explanation suggested.

2. Experimental Arrangements.

The apparatus used in the work is the same as that used by the author in an investigation on the intensity of the light scattered in ether.[5] The benzene was sealed in a stout-walled uniform glass bulb of about 1.2 inches internal diameter and the bulb was mounted in the center of an iron cross-tube (diameter 1.5 inches and each arm of the cross 15 inches long). The ends of the tube were closed with glass windows and it could be heated electrically by passing a current through a coil of nichrome wire wound uniformly over it. Temperatures could be maintained steady for long intervals of time to within half a degree. The benzene used was Merck's pure grade and was distilled five or six times in vacuo in the manner described by Martin.[6]

The intensity of the scattered light was determined by comparing the luminosity of a track of sunlight passing through it with a similar track in liquid ether kept in a rectangular glass bottle at the room temperature. The sunlight was focussed by two exactly similar lenses of the same focal length and provided with adjustable apertures at the center of the benzene bulb and at the center of the ether bottle. By means of two totally-reflecting prisms, the two tracks were brought

[1] Lord Rayleigh, Phil. Mag., Vol. 35, p. 373, 1918.

[2] Born, Deutsch. Phys. Gesell., Vol. 19, p. 243 (1917), and Vol. 20, p. 16 (1918).

[3] "Molecular Diffraction of Light," Calcutta University Press, 1922.

[4] Nature, July, 1922, page 11.

[5] Proc. Roy. Soc., Vol. 102, p. 154, 1922.

[6] Loc. cit.

side by side and their luminosities compared visually by means of a rotating sectored disc photometer.

The polarization of the light scattered at right angles to the incident beam was measured by means of a double-image prism and nicol. The double-image prism was mounted at the same height as the benzene bulb with its axis horizontal and pointing towards the bulb. It was first adjusted so that the two images of the horizontal track in the benzene were obtained in the same horizontal line and side by side with each other. The nicol was now inserted behind the double-image prism and so oriented that the vertical component was extinguished. On either side of this position, there is a position when the two images would be equal in intensity. If we denote the angle between these two equality-positions by 2θ, the ratio of the intensity of the horizontal component to that of the vertical is given by $\tan^2 \theta$.

3. Results.

The results regarding the scattering in the saturated vapor of benzene and in liquid benzene are collected in the following two tables.

Table I.

Scattering in Saturated Benzene Vapor.

S_t = Scattering at $t°$ C.
S_e = Scattering in liquid ether at 35° C.
ρ_t = density at $t°$ C.
r = Ratio of weak component to strong in the transversely scattered light.

Temperature $t°$.	$\frac{S_t}{S_e}$ Observed.	$\frac{S_t}{S_{182}}$.	$\frac{\rho_t}{\rho_{182}}$.	r (in per cent).	
				Observed.	Calculated.
35				7.2	
100				6.2	
182	0.95	1.00	1.00	3.5	3.2
204	1.56	1.64	1.48	3.4	2.8
228	3.00	3.15	2.25	2.5	2.2
247	4.9	5.14	3.00	2.0	2.0
267	11.9	12.5	4.5	1.5	1.2
280				0.9	

It will be seen that the intensity of scattering in both the saturated vapor and in the liquid increases rapidly with temperature becoming very large as we approach the critical temperature, and that in the case of the vapor, the increase is much more than in proportion to the density. The imperfection of polarization shows a diminution with increasing temperature tending to a very small value as we approach the critical point. In the last column of the two tables are shown the values of

imperfection of polarization calculated in the manner indicated in the next section.

TABLE II.

Scattering in Liquid Benzene.

Temperature $t°$ C.	$\frac{S_t}{S_0}$.	ρ.	
		Observed.	Calculated.
35	3.2	43	44
125	3.67	32	31
182	5.48	19	16
205	7.21	14	10.3
228	11.0	9.5	7.0
268	20.5	3.0	2.9
280		2.8	
283	102		

4. POLARIZATION OF THE TRANSVERSELY SCATTERED LIGHT.

The theory of light-scattering by gases consisting of isotropic molecules as developed by the late Lord Rayleigh and the general theory of scattering of fluids as developed by Einstein on the lines of Smoluchowski's work, based on the idea of accidental deviation of density in the fluid, predict a perfect polarization of the light scattered in a direction at right angles to the incident beam. Einstein's expression for the fraction of the incident light scattered per unit solid angle in a transverse direction by unit volume of a homogeneous fluid is given by

$$\frac{\pi^2}{18}\frac{RT\beta}{N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2, \qquad (1)$$

where T, β are the temperature and compressibility of the fluid, R is the gas-constant per gram-molecule, N the Avogadro-number, λ is the wave-length of the incident light and μ is the refractive index of the fluid. This reduces to Rayleigh's law in the case of gases obeying Boyle's law and experiments at Calcutta on a number of substances both in the liquid and vapor states have established the general validity of this law.

In the case of most media, however, the transversely scattered light is only imperfectly polarized. This imperfection has been attributed to the anisotropy of the molecules and the general case has been recently discussed by Raman. In such a medium, there is an extra scattering which is for the most part unpolarized, due to the anisotropy of the molecules. If Ω_0 denote the scattering arising from the fluctuations of density, $4\Omega_1$ the unpolarized scattering arising from molecular anisotropy and Ω_2 the polarized scattering due to the same cause, the ratio of the weak

component to the strong in the transversely scattered light is given by

$$r = \frac{2\Omega_1}{\Omega_0 + \Omega_2 + 2\Omega_1} \tag{2}$$

In the case of a gas obeying Boyle's law, Ω_2 has the value $\frac{1}{3}\Omega_1$. The extra contribution from molecular anisotropy leads to an increased scattering in the ratio

$$\frac{6(1+r)}{6-7r}. \tag{3}$$

We shall assume this to be true generally.

If the molecules have absolutely random orientations, Ω_1 should be proportional to the number of molecules per unit volume. Since in the case of liquids and vapors, on rise of temperature, Ω_0 increases at a much larger rate than the density (in liquid the density actually decreases), the ratio $2\Omega_1/(\Omega_0 + \frac{7}{3}\Omega_1)$ should get smaller and smaller and reach a minimum value at the critical point where the value of Ω_0 is a maximum. We can easily deduce a quantitative relation between the intensity of the transversely scattered light and its imperfection of polarization. From equation (2), when $\Omega_2 = \frac{1}{3}\Omega_1$,

$$\Omega_0 = \frac{6-7r}{3r}\Omega_1,$$

and since $\Omega_1 = k\rho$, where ρ is the density of the substance,

$$\Omega_0 = \frac{6-7r}{3r}k\rho,$$

and the total scattering

$$S = \Omega_0 + \frac{13}{3}\Omega_1$$
$$= \frac{1+r}{r}\cdot 2k\rho;$$

$$\therefore \frac{S}{\rho}\frac{r}{1+r} = 2k, \text{ a constant.} \tag{4}$$

In the last column of Tables I. and II. are given the values of r calculated from this relation. The constant k was calculated from the intensity and polarization of the transversely scattered light in saturated benzene vapor at room temperature. The imperfection of polarization was measured in an apparatus similar to that used by Lord Rayleigh, the vapor being illuminated by means of a strong beam of sunlight. The value of r was found to be 7.2 per cent as against Lord Rayleigh's value 6 per cent. The intensity at the room temperature was calculated, assuming the validity of the Rayleigh law of scattering (to which the

Einstein law reduces when the vapor is sufficiently rare) and applying the correction for the admixture with unpolarized light. The agreement between the calculated and observed values is satisfactory.

5. Calculation of the Intensity of the Transversely Scattered Light.

For calculating the intensity of the transversely scattered light according to the Einstein-Smoluchowski formula, the refractive index and the compressibility of the medium have to be known. The refractive index can be calculated, using Lorentz's relation $(\mu^2 - 1)/(\mu^2 + 2)\rho = 0.3423$ [1] for benzene (for the F line). There are no data for the compressibility of the liquid [2] or the vapor for the temperatures at which these experiments were made, but the compressibility of the vapor can be calculated from Dietrici's equation of state, viz.,

$$p = \frac{RT}{v - b} e^{-\frac{a}{RTv}} \tag{5}$$

with an empirical correction which can be determined in the manner described below. From (5)

$$\frac{1}{\beta} = -v\left(\frac{dp}{dv}\right)_t = p\left\{\frac{v}{v - b} - \frac{a}{RTv}\right\}$$

Putting in the values of a and b in terms of the critical constants $b = v_c/2$ and $a/RT = 4b = 2v_c$ this reduces to

$$-v\left(\frac{dp}{dv}\right)_t = p\left\{\frac{2v}{2v - v_c} - \frac{2v_c}{v}\right\} = \frac{2p}{v}\frac{(v - v_c)^2}{(2v - c_c)}, \tag{6}$$

where v is the specific volume of the saturated vapor and v_c is the critical volume (volume of 1 gram of the substance at the critical point).

To test the applicability of this equation, the values of the compressibility of the saturated vapors of ether, isopentane and carbon dioxide were calculated and the values compared with the actual values obtained from the isothermal curves. The actual value of the compressibility is found to be larger than that given by equation (6), the ratio of the actual compressibility to that derived from (6) lying in the neighborhood of 1.25 over a large range. This ratio is plotted against the reduced temperatures. The points for the three different substances lie practically on the same curve, and from 0.8 T/T_c to 0.96 T/T_c the ratio lies near 1.25. In order to calculate the isothermal compressibility

[1] Landolt-Bornstein Tabellen, 1912, p. 1031.

[2] Except for the liquid up to 100°. For this case, the observed values of the scattering agree with the calculated.

of the saturated vapor of a substance for which the necessary isothermal pressure volume data are not available, we may multiply the compressibility given by equation (6) by the corresponding factor obtained from the curve. Calculating in this way, I find that the scattering in benzene vapor at 267° C. is 10 times that of liquid ether at 35°, while the observed value is 11.9 times. At other temperatures, the observed values are even higher than the calculated ones. This may be due either to the inapplicability of the above method of calculating the compressibility, or to the presence of a trace of impurity in the benzene which would give rise to an additional concentration scattering. The writer hopes to repeat the intensity measurements with carefully purified benzene.

This does not, however, in any way invalidate the main conclusion of the paper, namely, the proportionality of the unpolarized part of the scattered light to the density. The theoretical basis for this rests upon the assumption of the random character of the orientation of the molecules and the agreement of the experimental and theoretical values of the imperfection of polarization supports the assumption. This relation may not be true in the case of all liquids; with liquids whose molecules behave like electrical di-poles, the orientations are certainly not likely to be *at random*. Experiments on the polarization of the transversely scattered light with other liquids and over a large range of temperature are likely to furnish valuable information on the mutual influence of molecules in liquids.

In conclusion, I have much pleasure in recording my thanks to Prof. C. V. Raman under whose inspiring guidance the work described above was carried out in the laboratory of the Indian Association for the Cultivation of Science.

210 Bowbazaar Street,
Calcutta,
August, 1922.

Addendum.

A question has been raised as to the mean wave-length to be adopted in calculations when using composite light like sunlight for scattering experiments. In the above paper, the wave-length of the F line has been adopted. The influence of the wave-length of the incident light enters in two ways: (1) directly in the λ^{-4} factor and (2) indirectly through its influence on μ. When comparing two substances as regards their scattering, the effect of the first and dominant factor is identical in the two cases; that of the second depends on the dispersive powers of

the two substances. The values of $(\mu^2 - 1)^2(\mu^2 + 2)^2$ for liquid benzene and liquid ether at 20° C have been tabulated below:

Liquid Benzene at 20° C.

λ.	C 6,563 A.	D 5,893 A.	F 4,861 A.	G′ 4,340 A.
μ	1.4965	1.5011	1.5133	1.5236
$(\mu^2 - 1)^2(\mu^2 + 2)^2$	27.76	28.22	30.48	32.53

Liquid Ether at 20° C.

λ.	C 6,563 A.	D 5,893 A.	F 4,861 A.	G′ 4,340 A.
μ	1.3519	1.3538	1.3580	1.3607
$(\mu^2 - 1)^2(\mu^2 + 2)^2$	10.05	10.16	10.56	10.77

In benzene, the more dispersive substance, the difference between adopting the wave-length of the F line and that of the G′ line, for example, comes to nearly 6 per cent. At higher temperatures and for the vapor, the effect would be less and when we remember that our standard of comparison, ether, has itself a higher refractive index towards the violet, the difference between adopting the values of μ_F and $\mu_{G'}$ reduces to 4 per cent.

As regards the intensity of the scattered light in different parts of the spectrum, it will depend partly on the distribution of energy in the incident light and partly on the law of scattering. Adopting Abbot's values for the energy-distribution in sunlight, and assuming that the energy in the scattered light is proportional to λ^{-4}, the following are the relative values of the scattered energies:

λ in A.U.	Incident Energy I in Arbitrary Units.	$I\lambda^{-4}$.
6,000	5,050	3.9×10^{21}
5,400	5,700	6.7 "
5,200	5,900	8.1 "
5,000	6,080	9.7 "
4,800	6,250	11.8 "
4,400	5,820	15.5 "
4,000	4,350	17.0 "
3,800	3,750	18.0 "
3,500	2,700	18.0 "

The effect of the dispersion of the substance is to increase the relative importance of the radiations of shorter wave-length and more for a substance of larger than for one of smaller dispersion.

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We have now to consider the visual effect of the scattered light. For ordinary luminosities, the maximum visual effect is produced by rays in the neighborhood of 5,500 A; but for the weak luminosities such as we here deal with, owing to the Purkinje effect, the region of maximum sensitiveness is shifted towards the blue, the shift being a function of the luminosity. Taking everything into account, the effective wave-length of the scattered light is probably a little farther on toward the violet than F; but considering the uncertainties in our knowledge of the luminosity-curves for weak illuminations and the smallness of the error when we use *scattered light for comparison*, the error introduced by adopting the wave-length of the F line for the calculations is not of a serious nature.

CALCUTTA,
November 28, 1922.

The Molecular Scattering of Light in Carbon Dioxide at High Pressures.

By C. V. Raman, M.A., D.Sc, Palit Professor of Physics in the Calcutta University, and K. R. Ramanathan, M.A., Assistant Lecturer, University College, Rangoon.

(Communicated by Dr. G. T. Walker, F.R.S.—Received June 7, 1923.)

1. *Introduction.*

The investigation described in this paper was undertaken in order to test theories of light-scattering by quantitative observations on carbon dioxide, under pressures ranging from 1 to 100 atmospheres, and temperatures from 0° C. to 50° C. The work includes a study of the following cases :—(1) the scattering of light by the unsaturated vapour ; (2) by the saturated vapour in thermal equilibrium with the liquid ; (3) by the liquid under the pressure of its own vapour ; (4) by the liquid under impressed pressure higher than the vapour tension ; (5) by the substance in the vicinity of the critical state ; and (6) by the substance in the gaseous state above the critical temperature.*

* The cases in which the fluid is superheated or supercooled and is in metastable equilibrium are not dealt with here.

Proc. Roy. Soc. A 104, 357–368, 1923.

Carbon-dioxide was chosen as a suitable substance for a comprehensive study of this kind for several reasons. The fact that it can be obtained commercially in cylinders in a practically pure condition greatly simplifies the experimental technique, and any pressure within the limits mentioned can be obtained without the use of special compressors. Then, again, the necessary pressure-volume data for the vapour and the gas are available from the work of Amagat* and for the liquid from that of Jenkin,† and the variation of its refractive index with density has also been fully studied by various investigators, notably by Phillips.‡ The existence of these data makes a theoretical calculation of the light-scattering possible. Further, carbon dioxide at atmospheric pressure shows a marked imperfection in the polarisation of the transversely scattered light, the ratio of the weak to the strong component of polarisation in the visual region of the spectrum being 10·6 per cent. Hence, it is a very convenient substance for studying the effect of variations of temperature and pressure on the state of polarisation of the scattered light.

Another reason why we felt impelled to take up a careful study of the scattering of light in carbon dioxide was that certain results obtained by Lord Rayleigh with this gas§ were, as has already been pointed out by us,‖ anomalous and stood in need of explanation. Rayleigh determined the intensity of the light scattered by carbon dioxide vapour contained in a steel cross-tube provided with glass windows and kept in communication with a steel cylinder containing liquid CO_2 at 21° C. He found the scattering to be 102 times stronger than that of CO_2 at atmospheric pressure and inferred that the scattering power was proportional to the density within the limits of experimental error. According to the Einstein-Smoluchowski formula, however, the scattering power should have been much larger, about 800 times that of CO_2 at atmospheric pressure.

With regard to this discrepancy, it should be mentioned that Rayleigh's assumption that the density of the gas in his observation tube was equal to that of the saturated vapour at 21° C., is open to question. It is mentioned in his paper that the observation tube was leaky, and that a gauge in the communication tube from the supply cylinder indicated only 50 atmospheres, while according to the measurements of Andrews the saturation

* Amagat, 'Ann. Chem. Phys.,' (6), vol. 29, p. 52 (1893).

† Jenkin, 'Proc. Roy. Soc.,' A, vol. 98, p. 170.

‡ Phillips, 'Proc. Roy. Soc.,' A, vol. 97, p. 225.

§ Lord Rayleigh, 'Proc. Roy. Soc.,' A, vol. 95, p. 155.

‖ 'Molecular Diffraction of Light' (Calcutta University Press), p. 61 (1922); also Phil. Mag.,' Jan., p. 113 (1923).

pressure at 21° C. is 60 atmospheres. From the diagram given in Rayleigh's paper, it is noticed that after passing the pressure gauge the gas had to filter through a steel tube tightly packed with cotton-wool, which must have greatly impeded the inflow of the gas into the observation tube to replace that lost by leakage, and hence the density of the gas whose scattering power was measured was in all probability considerably less than that of the saturated vapour. If we assume that the pressure in the observation tube was somewhat less than that shown by the gauge and was, say, 45 atmospheres, the scattering power, if it were proportional to the density, would only have been about 60 times that of CO_2 at atmospheric pressure at the same temperature, while according to the Einstein-Smoluchowski theory of scattering, it would be about 125 times. The experimental result, rightly interpreted, thus tends to support the Einstein law of scattering, and not the Rayleigh law. The matter, however, appeared sufficiently important to justify a careful re-examination, with apparatus so designed that no uncertainty as to the actual density of the vapour arises.

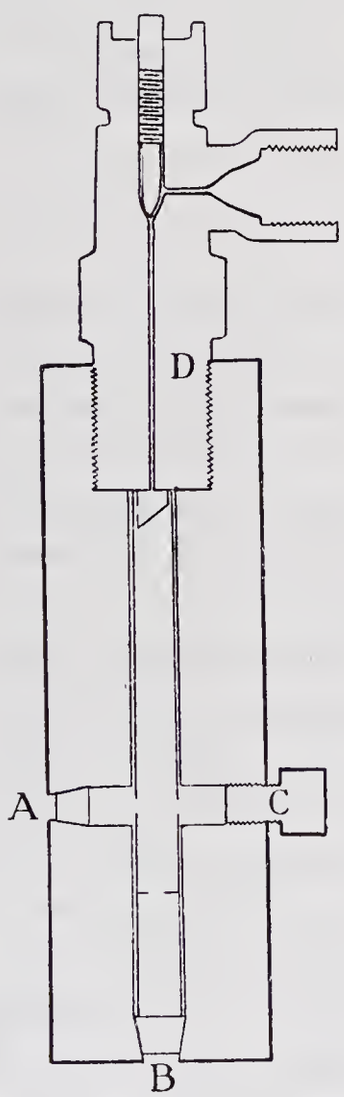
2. *Experimental Arrangements.*

In the present investigation, two distinct series of observations were made. In the first set, the scattering medium was CO_2 (vapour or liquid as the case may be) enclosed in sealed glass bulbs, thus avoiding all uncertainty regarding the density of the fluid used. A spherical bulb a little over 1 cm. in diameter was blown at one end of a stout walled capillary tube with rather a wide bore. The tube was carefully dried and exhausted, and dry CO_2 was introduced into it while immersed in liquid air. When the requisite quantity of carbon dioxide snow had condensed, the tube was sealed off leaving about 5 cm. attached to the bulb as a stem. Separate bulbs were prepared for the liquid and the vapour containing respectively an excess of the liquid and of the vapour. To prevent the bulbs bursting when the temperature is raised, sufficient volume for expansion is allowed in the stems attached to them. On removal from the liquid air, the carbon dioxide liquefies under the pressure.

The bulb and attached stem are completely blackened over with paint except for two tiny windows, one on either side of the bulb, for entry and exit of a narrow out powerful pencil of sunlight, and an aperture at the base of the bulb for observation of the scattered light. The stem with its bore forms a black cave against which the track of the beam through the CO_2 liquid or vapour, as the case may be, can be conspicuously observed. The bulb is completely immersed inside a water-bath with plate-glass slides, the rear-

walls being blackened so as to provide a dark field for observation. The temperature of the bath is regulated by adding either lumps of ice or hot water as desired. The brightness of the track of light is compared with that in another sealed tube containing a suitable dust-free liquid, like ether or benzene, or in a slab of optical glass, which serves as a standard and is also immersed in the bath, the same pencil of light passing through both. A rotating sector photometer with double disc placed in front of the cell enables the visual intensities of the two tracks to be equalised and their ratio thus to be determined.

Sealed bulbs, while convenient in many ways, are rather unsatisfactory optically when feeble light-scattering has to be measured, owing to the unavoidable reflections from the walls of the small-sized bulbs, which alone can sustain the high pressures. They are, therefore, not suitable for unsaturated vapours. It is also not possible with bulbs to work at pressures higher than the vapour-tension at the given temperature. Further, owing to the convergence of the light by the spherical walls, errors are also introduced in the photometry. In order to avoid these difficulties, in the second series of experiments, the simple form of apparatus shown was developed by the authors. This can safely withstand very high pressures and is suitable for the study of light-scattering in gases and liquids.



The observation tube consisted of a massive solid steel cylinder, 20 cm. long and 6·5 cm. in diameter, in which were drilled two cylindrical conical-ended holes, A and B, one axial and the other diametral. Two thick glass windows were ground in at A and B, the former to admit the primary beam of light and the latter for the observation of the scattered track. After the glass windows had been ground in, a tube with apertures for the entry of the primary beam and observation of the scattered light was put in place within the steel cylinder. This tube and the steel cylinder were enamelled black, a pin-valve was fitted to the end D, and the opening at C was closed up. To secure a good black background, a plate of black glass was fitted at an

angle of 45° inside the cylinder as shown. The observation tube could be connected to a pressure gauge and to the supply cylinder containing CO_2. Stopcocks placed on either side of the pressure gauge served to cut off its connection either with the observation tube or the supply cylinder as desired.

That the readings of pressure given by the gauge were reliable was tested in the following manner. The observation cylinder was *partly* filled with liquid and kept in communication with the gauge, the connection with the supply cylinder being cut off. The readings of the gauge were taken corresponding to different temperatures of the observation cylinder and were found to agree with the saturation pressures at those temperatures given by Amagat. The supply cylinder (which had been tested to stand 200 atmospheres) was placed in a vessel containing water, and by adjustment of the temperature of the water, pressures up to 100 atmospheres could be reached. The observation tube was placed in a rectangular glass vessel containing water, and its temperature could be kept constant at any desired value between 5° C. and 50° C. The observation cylinder and connecting tubes were evacuated before admission of carbon dioxide. The evacuation and re-admission of CO_2 were repeated until the track appeared a good blue with no evidence of dust particles.

For measurements of the scattering in saturated vapour, a shallow layer of liquid was allowed to condense at the bottom of the observation cylinder and the pin-valve at D closed. After a sufficient time had elapsed for the attainment of equilibrium, the intensity of the scattered light was compared with that in a standard substance as usual. For observations in the liquid in equilibrium with the vapour, the liquid was allowed to fill up more than three-fourths of the observation cylinder. The measurements of the scattering power in these two cases gave results in conformity with those obtained with the sealed bulbs.

3. *Experimental Results : Intensity of Scattering.*

(*a*) *Unsaturated Vapour.*—For experiments on unsaturated vapour, the steel observation tube was cut off from the supply cylinder, and by blowing off gas through an auxiliary outlet, any desired pressure below that of saturation could be got. The following table gives the intensity of scattering at different pressures at 30° C. in terms of the scattering of CO_2 at 0° C. and 76 cm. pressure.

Table I.

Pressure in atmospheres.	Density / Density at N.T.P.	Reciprocal of compressibility in atmospheres.	Density scattering (Einstein formula).	Density scattering corrected for anisotropy.	Observed scattering.
15	14·5	13·5	17·2	21·3	22
20	20·0	18·7	23·4	29·0	33
30	32·1	23·0	49	59	54
40	47	29·4	65·2	77	83
50	64·5	31·5	123	144	140
55	75·7	30·2	180	207	197
60	89·7	27·9	276	315	307
65	109	22·9	514	576	665
68	127	19·1	847	940	1078

It will be noted from columns 2 and 6 that the observed scattering is much larger than in proportion to the density. The values in column 4 are calculated according to Einstein-Smoluchowski formula. When the molecules are anisotropic there is an extra scattering, the "orientation scattering," whose magnitude depends on the properties of the molecule and on the state of aggregation of the fluid. Its value has been worked out in a recent paper,* and the total intensity at a distance d of the light transversely scattered by a unit volume of the fluid in any condition is given by

$$\frac{I_0}{d^2}\left[\frac{\pi^2}{18}\frac{RTf}{N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2+\frac{\pi^2}{2n_0\lambda^4}(\mu^2-1)^2\frac{r_1(9+4\gamma)}{6-7r_1}\right],$$

where n_0 is the number of molecules per unit volume in the fluid, r_1 is the ratio of the weak component to the strong in the light transversely scattered by the substance in the state of vapour at very low pressures, and γ denotes $\frac{RT\beta}{N}n_0\left(\frac{\mu^2+2}{3}\right)^2$. The other symbols have their usual meanings. The total scattering given by this formula is given in column 5 for comparison with the observed intensity of scattering given in column 6. The agreement is good except in the vicinity of the critical temperature, where uncertainties in temperature and impurities in the substance have a very great effect.

* K. R. Ramanathan, 'Proc. Ind. Assoc. for the Cultivation of Science,' vol. viii, pp. 1-22 (1923).

Table II.

(*b*) *Saturated Vapour.*—

Temperature.	Density / Density at N.T.P.	Reciprocal of compressibility.	Density scattering (Einstein formula).	Density scattering corrected for anisotropy.	Observed scattering.	Remarks.
0°	48	20·6	92	106		
5°	57	21·5	120	140	102	Bulb.
10°	68	21·9	180	205	195	,,
15°	80	21·0	300	340	347	,,
20°	96	19·7	560	620	567	,,
24°	112	16·0	920	1000	1010	,,
					1050	Cylinder.
25°	121	15·0	970	1067	1190	Bulb.
26°	126	13·7	1210	1330	1920	,,
					1860	Cylinder.
28°	140	10·0	2010	2190	3630	Bulb.
					3490	Cylinder.
30°	169	5·9 (?)	5100	5500	8000	Bulb.

Table III.

(*c*) *Liquid in Equilibrium with Vapour.*—

Temperature.	Density. / Density at N.T.P.	Reciprocal of compressibility in atmospheres.	Density scattering (Einstein formula).	Density scattering corrected for anisotropy.	Observed scattering.	Remarks.
5°	448	700	380	494	360	Bulb.
10°	432	530	480	600	463	,,
					500	Cylinder.
15°	411	372	618	760	630	Bulb.
					730	Cylinder.
20°	387	220	905	1086	980	Bulb.
					1000	Cylinder.
23°	369	146	1240	1450	1280	,,
25°	355	110	1540	1786	1880	Bulb.
27°	340	65	2340	2620	2950	,,
29°	317	25	5080	5590	6200	,,
30°	302	15	7500	8350	11000	,,
31°	271	4	28700	31000	35000	,,

The compressibilities at temperatures higher than 20° were obtained in the following way. The reciprocals of the compressibility at the saturation points at temperatures below 20° C. (taken from Jenkin's paper) were plotted against the temperature, and taking the reciprocal of the compressibility at the critical point to be zero, a smooth curve was drawn through these points.

Table IV.

(*d*) *Liquid CO_2 at Higher Pressures.*—

Temperature.	Pressure in atmospheres.	Density. Density at N.T.P.	Reciprocal of compressibility in atmospheres.	Density scattering (Einstein formula).	Density scattering corrected for anisotropy.	Observed scattering.	Remarks.
15°	51	416	387	618	760	663	
	68	430	567	458	575	522	
	76	436	674	374	482	470	
	82	440	773	354	464	428	
25°	Saturation.	355	110	1540	1786	2100	
	68	373	195	976	1122	1650	
	74	383	243	827	968	1200	
	83	397	309	678	834	778	
	92	407	486	483	599	600	
30·5°	Saturation	289	10	10400	11300	22500	
	72·5	314	35	3600	3900	5480	These calculated values refer to 30° C.
	76·5	343	83	1880	2106	2610	
	84·0	366	155	1185	1351	1097	
	86·5	372	179	1063	1220	940	

(*e*) *Scattering above the Critical Temperature.*—

Table V.—(i) Scattering at 35° at different pressures.

Pressures in atmospheres.	Density / Density at N.T.P.	Reciprocal of compressibility in atmospheres.	Density scattering (Einstein formula).	Density scattering corrected for anisotropy.	Observed scattering.
61	85	33·5	220	253	290
67	104	27·6	401	453	680
72	125	21·2	780	866	1170
77·5	177	13·3	2580	2830	3200
81	275	13·8	5170	5220	4230
87	330	72·1	2010	2250	1750
91					1430

Table VI.—(ii) Scattering at constant density (0·320 gm./cc.) at different temperatures above the critical temperature.

Temperature.	Density / Density at N.T.P.	Reciprocal of compressibility in atmospheres.	Density scattering (Einstein formula).	Density scattering corrected for anisotropy.	Observed scattering.
32°	165	8·4	3420	3730	4550
35°	165	14·1	2060	2266	2730
40°	165	19	1550	1705	1620
50°	165	22	1380	1520	1410

4. *Polarisation of the Scattered Light: Theory and Experimental Results.*

In previous papers,* the authors have discussed the influence of the physical condition of the substance on the imperfection of polarisation of the transversely scattered light. An exact investigation of the problem has been worked out† on the assumption of anisotropic molecules with three principal axes. It leads to the formula

$$r = \frac{2f}{f+\gamma g},$$

where r is the ratio of the weak component to the strong in the transversely scattered light, and γ has the meaning already indicated in the previous section. When the substance is in the gaseous state at low pressure and Boyle's law holds good, $\gamma = 1$ and r assumes the value $2f/(f+g)$ which has been already denoted by r_1.

Also

$$g - \frac{4}{3}f = \frac{9}{16\pi^2 n_0^2}\left(\frac{\mu^2-1}{\mu^2+2}\right)^2.$$

The formula indicates that when the scattering is very large, *e.g.* in the neighbourhood of the critical point, it is almost completely polarised ; while in other cases, *e.g.* when the substance is in the liquid state much below the critical temperature, the polarisation is markedly less perfect than in the scattering by the vapour at low pressures. While these indications of theory are in qualitative agreement with facts, it is found that in the case of many liquids, there are considerable differences between theory and observation in the quantitative data, indicating that the assumption of a random orientation of the molecules made in the theory is not generally valid. This makes it all the more important that as many different substances as possible should be examined.

The problem of determining accurately the state of polarisation of light scattered by a fluid under high pressures is not without serious experimental difficulties. The principal source of error is the unavoidable strain and consequent selotropy of the glass walls or the glass window through which the scattered light is observed. If the strain were perfectly symmetrical about the direction of observation no error would arise, but this condition is not easy to secure, especially when a conical glass window has to be pressed home into a metal recess provided for it to make it perfectly leak-tight. Small sealed bulbs are also not quite suitable in this type of work, owing to the very

* C. V. Raman and K. Seshagiri Rao, 'Phil. Mag.,' vol. 45, p. 625. K. R. Ramanathan, *loc. cit.*

† K. R. Ramanathan, *loc. cit.*

imperfect background which they furnish for observing the fainter component of polarisation. In view, however, of the fact that even an approximate determination of the state of polarisation under different conditions would be of interest, attempts were made to measure the effect with the apparatus used by the authors. The vapour or liquid inside the chamber was illuminated by a narrow horizontal beam of sunlight and on examination with a double-image prism set so as to transmit vertical and horizontal vibration, it was found that even near the critical point both images were bright, but that across the weaker one there was an intense black band running obliquely. The glass window was obviously under strain, but by isolating the portion of the glass wall transmitting the central portion of the black band alone by means of a narrow slit (nearly 1 mm. wide) placed in contact with the window, measurements of polarisation were made as usual with a double-image prism and nicol.

The following tables contain a summary of the results.

5. *Imperfection of Polarisation.*

Table VII.

(i) *Unsaturated Vapour at* 30° C.

Pressure in atmospheres.	Ratio : $\frac{\text{Weak component}}{\text{Strong component}}$	
	Observed.	Calculated.
	Per cent.	Per cent.
30	9	8
40	8	6
50	6	4·9
60	4·5	3·1
65	4	2

(ii) *Saturated Vapour.*

Temperature.	Ratio : $\frac{\text{Weak component}}{\text{Strong component}}$	
	Observed.	Calculated.
15°	5·8	2·6
20°	4	2·1
25°	3	1·2
30°	1·5	0·3

iii) *Liquid in Equilibrium with Vapour.*

Temperature.	Ratio : Weak component / Strong component	
	Observed.	Calculated.
10°	14	10·5
15°	10	7
20°	8	6
25°	5	3·8
28°	3	1·4

(iv) *Liquid under Higher Pressures.*

Temperature.	Pressure in atmospheres.	Ratio : Weak component / Strong component	
		Observed.	Calculated.
20°	92	13	14
	80	10	9
25°	90	9	8

The observed values are uniformly a little too high. This is probably due to the fact that the slit used has a finite width, and transmits light to a small distance on either side of the centre of the black band. The actual course of values, however, follows the indications of theory.

6. *Summary and Conclusion.*

The paper describes a simple form of apparatus which enables the intensity and state of polarisation of the light scattered by gases and liquids at high pressures to be measured. Results obtained with carbon dioxide are given, the noteworthy features being the following :—

(1) The scattering in carbon dioxide in the condition of unsaturated vapour below the critical temperature is not proportional to the density, but increases much more rapidly as the saturation pressure is approached, and the polarisation of the transversely scattered light becomes sensibly more and more *perfect.*

(2) The scattering in the saturated vapour and in the liquid phase in equilibrium with it has also been studied. When the liquid is further com-

pressed by application of pressure in excess of the vapour tension, its light-scattering power shows a striking diminution, and the polarisation becomes markedly more *imperfect*.

(3) Above the critical temperature, the scattering power at first increases with rise of pressure, reaches a maximum, and diminishes again.

(4) Except very close to the critical temperature, the experimental results agree well with the Einstein-Smoluchowski theory of scattering when the effect of molecular ælotropy is taken into account.

We have, in conclusion, to express our cordial thanks to Messrs. The Lightfoot Refrigeration Company, of Calcutta, who gave us much assistance in fitting up the high-pressure apparatus and in other ways.

ON THE VISUAL AND PHOTOGRAPHIC ALBEDO OF THE EARTH

By K. R. RAMANATHAN

ABSTRACT

The visual and photographic albedo of the earth.—This subject, previously treated by H. N. Russell and C. G. Abbot, is here discussed afresh in the light of Luckiesh's recent measurements of the visual brightness of earth-areas as seen from an aeroplane and Raman's theory of the color of the sea as originating from the molecular scattering of light in deep water. The effects of molecular scattering by the atmosphere and the sea are considered in detail with reference to the spectral distribution of the scattered light. The computed visual albedo comes out to be 0.46, and the photographic 0.58, in close agreement with the astronomical values 0.45 and 0.6 respectively.

INTRODUCTION

A valuable discussion of the photometric measures of the albedo of the earth was put forward by H. N. Russell,[1] who came to the conclusion that the visual albedo of the earth according to Bond's definition, as deduced from Very's observations of earth-shine on the moon, was 0.45 and the photographic albedo was 0.6. Further, Abbot[2] from radiation measurements and a consideration of the physical characteristics of the earth, has computed the total energy albedo to be 0.37. The difference between the visual and photographic albedoes is considerable and it has been suggested that this is due to the fact that a part of the light diffused out by the earth arises from the molecular scattering of light in the earth's atmosphere. Since the publication of the papers referred to, two investigations have appeared which make it desirable to consider the problem of the earth's albedo afresh. Luckiesh[3] has published observations made during aeroplane flights of the visual albedo of different kinds of landscape and also inland and oceanic waters. Then again, Abbot, in his discussion of the albedo of water-covered areas, considered only the reflection of light at the *surface* of the liquid. In reality, we have also to consider the important part arising from the diffusion of light entering the water. A theory of the color of the sea as being due to the molecular scatter-

[1] *Astrophysical Journal*, **43**, 173, 1916.

[2] *Annals of the Smithsonian Astrophysical Observatory*, **2**, 161–163.

[3] *Astrophysical Journal*, **49**, 108, 1919.

Astrophys. Journ. 57, 177–184, 1923.

ing of light in deep ocean water has been put forward by C. V. Raman,[1] who has also pointed out the importance of the contribution which the scattered light from the sea would make to the albedo of the earth. In this paper, it is proposed to discuss the problem of the albedo, taking into account the spectral distribution of the molecular scattered light from the atmosphere and the sea.

We may divide the light going out of the earth into space as arising in the following ways:

1. Light molecularly scattered from the atmosphere above the region of dust;

2. Light scattered by the clouds;

3. Light scattered from the unclouded portions of the earth in the lower dusty regions of the atmosphere;

4. Light diffusely reflected from the earth's surface including the oceans.

Of these, the light molecularly scattered from the atmosphere and the sea would be richer in the shorter wave-lengths, and hence, on the aggregate, the returning light would be bluer than the incident.

LIGHT MOLECULARLY SCATTERED FROM THE ATMOSPHERE ABOVE THE REGION OF DUST

The discussions by F. E. Fowle[2] and L. V. King[3] of the extensive measurements of atmospheric transparency made by the Smithsonian Observatory have shown that in the region of wave-lengths shorter than 0.69 μ the loss of light on a clear day above the Mount Wilson level (1730 meters) could be accounted for almost entirely by the molecular scattering of light by the atmosphere.[4] The selective absorption exercised by the oxygen and water-vapor lies entirely in the region of wave-lengths longer than 0.70 μ and hence outside the visual and photographic regions. We shall take Mount Wilson level to be the upper limit of the region of dust. Abbot has given a table of intensities of energy in the normal solar spectrum outside the earth's atmosphere. From these and the values of the yearly mean dry-air transmission coefficients at Mount

[1] *Proceedings of the Royal Society*, A, **101**, 64, 1922. See also *Molecular Diffraction of Light*, published by the Calcutta University Press, 1922.

[2] *Astrophysical Journal*, **38**, 393, 1913.

[3] *Philosophical Transactions of the Royal Society*, A, **212**, 375, 1913.

[4] Except for a possible small selective absorption between 0.51 μ and 0.65 μ.

Wilson,[1] we can determine graphically, from the areas of the energy wave-lengths curve, the percentage of light lost in transmission in different regions of the spectrum. Between 0.45 μ and 0.68 μ which we may take to be the effective visual region, I find the percentage of energy lost on normal transmission to be 10, and, in the region between 0.35 μ and 0.45 μ which we may take to be the effective photographic region, the percentage is 24. We have now to consider the actual loss that occurs, taking into account the facts that at a large portion of the earth's surface the light is incident obliquely and that, on the average, a portion of the atmosphere above Mount Wilson level is always clouded. At the place where the sun's rays meet the earth at an angle i, the transmission coefficient is $a^{\sec i}$ where a denotes the same quantity for normal incidence. The quantity of light falling on the surface of a sphere of radius r between the angles i and $i+di$ is

$$2\pi r^2 I \sin i \cos i \, di ,$$

where I is the intensity of the incident light. The amount of light transmitted in the same range is this quantity multiplied by $a^{\sec i}$, and this, taken over the whole sphere is

$$2\pi r^2 I \int_0^{\frac{\pi}{2}} \sin i \cos i \, a^{\sec i} \, di . \qquad (1)$$

The integral does not seem to be capable of being easily evaluated; instead, it was done by graphical integration and the total loss in the visual region was found to be 17 per cent and in the photographic region 38 per cent. Assuming that half this amount would be reflected back to space, we get 8.5 per cent to be the visual, and 19 per cent to be the photographic albedo of the atmosphere above Mount Wilson, if it were entirely unclouded. Actually, however, according to Abbot,[1] about 60 per cent of the earth's cloudiness is above Mount Wilson level and since, on the average, 52 per cent of the earth's surface is always clouded, 31 per cent of the skies above Mount Wilson will be always covered by clouds. The distribution of clouds with height as given in Humphreys' *Physics of the Air*[2] is as follows:

1. Cirrus level—height above surface about 10 km
2. Cirro-stratus level—height above surface about 8 km

[1] Fowle, *Smithsonian Miscellaneous Collections*, 69, No. 3. [2] P. 309.

3. Alto-cumulus level—height above surface about 4 km
4. Cumulus level—height above surface about 1.5 km
5. Fog-level—ground

Of these, the first two would be comparatively thin and would transmit a large portion of the light. We may take the average cloud-height above Mount Wilson to be $5\frac{1}{2}$ km, corresponding to a level at which the pressure is half the sea-level pressure. Thus, the albedo due to the molecular scattering of the atmosphere above the dust-level would be as is shown in Table I.

TABLE I

	Visual	Photographic
From cloudless portion.....	0.69×8.5	0.69×19
From clouded portion.....	$0.31\times\frac{38}{63}\times8.5$	$0.31\times\frac{38}{63}\times19$
Total.....	7.5 per cent	17 per cent

We have assumed the fraction scattered from the clouded portion to be less than that from the unclouded, in the ratio of the pressure above the average higher cloud-level to the pressure at Mount Wilson. We have also neglected the scattering due to the moisture in the dustless region.

LIGHT REFLECTED FROM THE CLOUDS

According to Abbot's energy-measurements and Luckiesh's photometric observations, we shall take the average reflecting power of clouds to be 65 per cent. Since the average cloudiness of the earth is 52 per cent, we get, for the percentage of light reflected back from the clouds, the values given in Table II.

TABLE II

	Visual		Photographic	
	Percentage Incident	Percentage Reflected	Percentage Incident	Percentage Reflected
From higher clouds (average level 5.5 km)	$100-\frac{38}{63}\times8.5=95$	$0.31\times95\times0.65=19.1$	$100-\frac{38}{63}\times19=88.6$	$0.31\times88.6\times0.65=17.9$
From lower clouds (average level 1.7 km)	$100-8.5=91.5$	$0.21\times91.5\times0.65=12.5$	$100-19=81$	$0.21\times81\times0.65=11.1$
Total.....	.....	31.6	.....	29.0

Very little need be allowed from this for loss in transmission upward, for the diminution is due to scattering, and the scattered light would either go up or again get reflected from the clouds.

LIGHT SCATTERED FROM THE LOWER ATMOSPHERE

The light reflected from the lower atmosphere below the Mount Wilson level can be calculated as follows. From Abbot's data[1] for the mean coefficients of normal atmospheric transmission at Mount Wilson and Washington, the percentage of energy lost between the levels of the two stations is calculated for different wave-lengths, and an energy wave-length curve constructed with these data. From the area of the curve, it is found that in the region 0.45 μ–0.68 μ, 14 per cent of the energy is lost, and practically the same percentage between 0.35 μ and 0.45 μ. Assuming 20 per cent of this to be absorbed and half the remainder to be sent to earth and the other half back, we get 6 per cent to be the ratio of the light reflected back at normal incidence. Taking into account the fact that at a considerable portion of the earth the light is incident obliquely and that only 48 per cent of the earth is unclouded, the contribution of the lower atmosphere comes out to be nearly 4.5 per cent.

The above estimates agree very well with the careful visual photometric measurements of Kimball,[2] who found a mean transmission coefficient of 0.77 in clear weather, corresponding to the estimate here made of a loss of 10 per cent above Mount Wilson and 14 per cent below it.

LIGHT REFLECTED FROM THE EARTH'S SURFACE

Since more than three-fourths of the earth's surface is covered by seas, the most important contribution of the albedo from the surface of the earth would come from them. The deep blue color of the ocean waters has been explained by C. V. Raman[3] as originating from the molecular scattering of light within the water. The fraction of the incident energy scattered by unit volume of a homo-

[1] *Astrophysical Journal*, 34, 203, 1911.

[2] *Monthly Weather Review*, 43, 650, 1914; also H. N. Russell's article, *loc. cit.*

[3] *Proceedings of the Royal Society*, A, 101, 64, 1922.

geneous fluid like water is, for the most part, given by the Einstein-Smoluchowski expression

$$\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2\,, \qquad (2)$$

where β is the isothermal compressibility of the medium, μ its refractive index, N the Avogadro constant and λ the wave-length of the incident light. R and T have their usual meanings in kinetic theory. Since the amount of scattered light varies inversely as the fourth power of the wave-length, we can easily see why the blue end of the spectrum should predominate in the light returning from the water. Two other factors go to make the scattered light even a richer blue: one is the greater absorption in water of the red and yellow regions of the spectrum, and the other is an addition, to the light scattered in accordance with (2), of some unpolarized light which is greater in the violet end of the spectrum.[1] In his paper, Raman has given a table of the luminosity of deep ocean water for different wave-lengths in terms of the luminosity of a layer of dust-free air one kilometer thick when viewed transversely to the incident light. In calculating these values, he made use of the absorption coefficients of water obtained by Count Aufsess. Recently, W. H. Martin[2] has obtained fresh values for the absorption coefficients with pure, dust-free water, and Table III gives Raman's revised values for the luminosity of ocean water in terms of that of an atmosphere of dust-free air which would give an equal effect by lateral scattering.

TABLE III

LUMINOSITY OF OCEAN WATER

	Wave-Length in μ						
	0.658	0.602	0.590	0.578	0.546	0.499	0.436
Equivalent atmospheres of dust-free air	0.06	0.09	0.23	0.35	0.65	0.90	2.0

Confining ourselves to the region 0.45 to 0.68 μ, the fraction of incident light scattered comes out to be 0.06. Luckiesh's direct

[1] C. V. Raman, *Molecular Scattering of Light*, p. 55.

[2] *Journal of Physical Chemistry*, May, 1922.

determination of the "reflecting" power of the Atlantic, as measured from an aeroplane, gave an average value of 3.5 per cent. The difference is no doubt to be attributed to the fact that, in the above calculation, the absorption coefficient has been assumed to be equal to that of dust-free distilled water. Luckiesh makes it clear that 90 per cent of the light returning from the sea as viewed normally, is due to light diffused within it. The foregoing estimate refers to direct overhead observation. In an oblique direction, the molecular scattering would give rise to a greater luminosity, as a more extensive surface layer of water would come into operation, and, indeed Luckiesh has noticed that the brightness increases more than twice when the sea-surface is viewed at an angle of 45°.

Besides the molecular scattering, there is also the specular reflection to be taken into account, which would give rise to a reflection factor of about 3 per cent.

On the whole, we may put 8 per cent to be the fraction coming back from the ocean waters. As regards land areas, Luckiesh has obtained the following reflection factors for some typical surfaces: fields, 7.2 per cent; barren lands, 12.0 per cent; woods, 4.3 per cent. A snow-covered surface is known to reflect about 75 per cent of the incident light, but almost the whole of the snow-covered areas of the earth are near the poles, where only a small fraction of the sun's energy is received and where, moreover, a large part of the incident light would have been scattered by the atmosphere before reaching the earth. We may take, without much error, 12 per cent to be the average reflecting power of the land areas of the earth. Thus, the percentage of light scattered from the earth's surface in the visual region would come to be nearly $0.80(\frac{3}{4}\times 8+\frac{1}{4}\times 12)$, i.e., 7.2. Of this, allowing 30 per cent for loss on transmission through the atmosphere and remembering that only 48 per cent of the earth's surface is unclouded, we get 2.5 per cent to be the contribution of the surface of the earth to the visual albedo.

As regards the photographic albedo, the scattered light from the sea would contribute much more. An examination of Table III would show the enormous concentration of energy in the violet end of the spectrum. In the near ultra-violet, the light scattered from the sea is likely to be even stronger, since the absorption coefficient

of water gets smaller and smaller as we go to the region of shorter wave-lengths. But against this, it has to be said that the presence of motes would tend to increase the absorption. We have previously estimated the photographic albedo of the sky above Mount Wilson to be 0.19, and, from Table II, it is evident that we shall not be far wrong if we take the fraction of the incident energy scattered by the sea to be 0.30. With the usual allowance for the loss of energy of the incident and reflected rays on transmission through the atmosphere and the fact that a portion of the earth's surface is clouded, we get the photographic albedo due to the sea to be nearly 6 per cent. The land areas would contribute practically nothing to the photographic albedo except the snowy regions near the poles, whose effect may come to about 1 per cent. Thus, the aggregate photographic albedo due to the surface of the earth would come to nearly 7 per cent.

SUMMARY

TABLE IV

	Visual	Photographic
	Per Cent	Per Cent
Light scattered from the gases of the atmosphere above the dust level	7.5	17
Light reflected from the clouds	31.6	29.0
Light scattered from the lower atmosphere	4.5	4.5
Light reflected from the surface of the earth including the oceans	2.5	7.0
Total	46	57.5

The visual and photographic albedoes obtained above agree very well with the astronomical value 0.45 and 0.6. Considering the uncertainties in the estimation of the earth's albedo factors and the difficulties of photometric measurement of the earth-shine on the moon, the agreement is actually better than could have been anticipated.

In conclusion, I have great pleasure in expressing my thanks to Professor C. V. Raman for his suggestion of the problem and interest in the progress of the work.

University College, Rangoon
August 5, 1922

LVIII. *On the Colour of the Sea.* *By* K. R. Ramanathan, *M.A., Assistant Lecturer in Physics, University College, Rangoon, Burma* *.

1. *Introduction.*

In a recent paper †, Prof. C. V. Raman has put forward the theory that the deep blue colour characteristic of the larger part of ocean waters is due to the molecular scattering of light in water, and supported it by calculations of the intensity and quality of the light returned from deep water. He has shown that pure, dust-free water scatters light in accordance with a formula originally deduced by Einstein for the critical opalescence of fluids, and that molecular scattering by itself without the aid of any extraneous agency is sufficient to account for the return of a part of the incident light. The following investigation was undertaken in order to test how far actual sea-water comes up to the ideal dust-free condition, and to find how the waters in seas showing different colours vary from one another.

2. *Theoretical Discussion.*

Preliminarily, it is useful to consider what intensity and colour we should expect from a *perfectly absorptionless* dust-free ocean of infinite depth. In such a case, the diminution of intensity of light in its passage through the medium would be wholly accounted for by molecular scattering. Since there is no transformation of the incident energy, it would be entirely thrown back, and the returned light would be of the same quality as the incident ‡. Since the scattering coefficient varies inversely as the fourth-power of the wave-length, the depth of the medium responsible for the return of a certain percentage of blue light would be smaller than that responsible for the return of the same

* Communicated by Prof. C. V. Raman, M.A., D.Sc.

† C. V. Raman, Proc. Roy. Soc. A, vol. ci. p. 64 (1922). See also 'Molecular Diffraction of Light,' Calcutta University Press, 1922, chapter v.

‡ *Vide* Schuster, 'Theory of Optics,' Second Edition, p. 271.

Phil. Mag. 46, 543–553, 1923.

percentage of red light. Selective absorption, however, would modify the condition of affairs. The light of those wave-lengths for which the medium exercises a selective absorption would be gradually diminished in intensity as the light penetrates into the medium, and if the absorption is at all considerable, there would be very little of these radiations returned. Now, water is known to exercise a selective absorption in the red which gradually decreases as we proceed into the region of shorter wave-lengths. The most extensive measurements of absorption coefficients for water that we possess are those of Count Aufsess * between wave-lengths 658 $\mu\mu$ and 494 $\mu\mu$. Recently, W. H. Martin † has measured the absorption coefficients of water repeatedly distilled *in vacuo* for the mercury lines 578 $\mu\mu$, 546·1 $\mu\mu$, and 435·8 $\mu\mu$. As has been pointed out by Martin, there is an error in Aufsess's measurements, as he neglected to take into account the loss of light on reflexion at the glass surfaces at the ends of the absorption-tube. However, considering the length of tube which Aufsess employed (5·5 metres), the relative error involved is not large in the region of the red where the absorption is large. We shall therefore adopt Aufsess's values for the absorption coefficients in the red. In Table I. are shown the experimental values of the extinction coefficient γ, defined by $I=I_0e^{-\gamma x}$, where I_0 is the intensity of a parallel beam of incident light, and I is the intensity after traversing a thickness x of water. In the fourth column are shown the values of the extinction coefficients, if the extinction were due *solely* to molecular scattering. These are calculated according to the formula

$$\alpha=\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2\ \ddagger.$$

* Count Aufsess, *Ann. der Physik*, vol. xiii. (1904).

† W. H. Martin, Journ. Phys. Chem. xxvi. p. 471 (1922).

‡ *Vide* C. V. Raman, *loc. cit.* and 'Molecular Diffraction of Light,' chapter iv. p. 52.

This is derived on the assumption that the light scattered in a direction perpendicular to the incident beam is perfectly polarized. As a matter of fact, the transversely scattered light shows a defect in polarization. In addition to the polarized "Einstein scattering," there is an additional scattering due to the anisotropy of the molecules, which for the most part is unpolarized. If we take the latter also into account, the formula for the coefficient of extinction becomes

$$\alpha=\frac{2\pi^3}{9}\frac{RT\beta}{N\lambda^4}(\mu^2-1)^2(\mu^2+2)^2\left\{\frac{4}{3}+\frac{r}{1-r}\right\},$$

where r is the ratio of the weak component to the strong in the transversely scattered light, and the values of the extinction coefficients come out to be $8{\cdot}2\times10^{-6}$, $1{\cdot}08\times10^{-5}$, $1{\cdot}38\times10^{-5}$, $1{\cdot}76\times10^{-5}$, and $5{\cdot}0\times10^{-5}$ for the wave-lengths given above.

TABLE I.

Wave-length.	Absorption coefficient.	Author.	Extinction coefficient due to scattering alone.
658.....	$3{\cdot}2 \times 10^{-3}$	Aufsess.	$7{\cdot}5 \times 10^{-6}$
612.....	$2{\cdot}33 \times 10^{-3}$	Aufsess.	$9{\cdot}9 \times 10^{-6}$
578.....	$6{\cdot}4 \times 10^{-4}$	Martin.	$1{\cdot}3 \times 10^{-5}$
546·1	$3{\cdot}4 \times 10^{-4}$	Martin.	$1{\cdot}6 \times 10^{-5}$
435·8	$1{\cdot}2 \times 10^{-4}$	Martin.	$4{\cdot}3 \times 10^{-5}$

In the red, yellow, and green, up to 546 $\mu\mu$, practically the whole of the extinction is due to absorption, while in the blue and the violet, scattering takes away an appreciable part. The intensity of the incident radiation is reduced to one-half at a depth of approximately 2 metres for 658 $\mu\mu$, 10 metres for 578 $\mu\mu$, 20 metres for 546 $\mu\mu$, and 60 metres for 435·8 $\mu\mu$. Taking primary scattering alone into account and considering the directions of incidence and observation to be vertical, the total observed brightness due to an infinite depth of water can be easily shown to be $B/\gamma\lambda^4$ *, where the scattering coefficient in a transverse direction has the value

$$B = \frac{\pi^2}{18} \frac{RT\beta}{N\lambda^4} (\mu^2 - 1)^2 (\mu^2 + 2)^2.$$

We can now see why the returned light should be specially deficient in the red, yellow, and green. The increase in absorption goes hand in hand with the decrease in scattering, and the two together serve practically to eliminate the longer wave-lengths. The following Table gives the course of values of $B/\gamma\lambda^4$:—

λ in $\mu\mu$.	658.	612.	578.	546.	436.
$B/\gamma\lambda^4$.....	$1{\cdot}4 \times 10^{-4}$	$2{\cdot}5 \times 10^{-4}$	$1{\cdot}2 \times 10^{-3}$	$2{\cdot}8 \times 10^{-3}$	$2{\cdot}1 \times 10^{-2}$

In order to obtain the resultant colour of the sea, we have only to compound the effects of different wave-lengths in their proper proportions. The intensities for the different wave-lengths throughout the visible spectrum can be obtained

* C. V. Raman. *loc. cit.* If the anisotropic scattering is also taken into account this would become $B(1+r)/\gamma\lambda^4$.

by the above formula, and their colour effects expressed in terms of the spectrum colours 630·2 $\mu\mu$, 538·1 $\mu\mu$, and 456·9 $\mu\mu$, using the values given by the late Lord Rayleigh in his paper on "The Colours of Thin Plates"*. The resultant colour is found to have the composition $1{\cdot}56 \times 10^{-3}$ red, $2{\cdot}49 \times 10^{-2}$ green, and $9{\cdot}53 \times 10^{-2}$ violet, and approaches the spectrum colour 475·0 $\mu\mu$, being very near the indigo of the second order in the colours of thin plates. The inclusion of secondary scattering would reduce the effective depth of the sea from which the scattered light returns; it would also serve to further diminish the intensities of the red and yellow, for which the absorption is strong.

It is obvious that the presence of any dissolved matter giving rise to extra absorption in any particular region of the spectrum would cause a corresponding diminution of the intensity of the returning light in that region of the spectrum.

Let us now consider the effect of suspended matter. It would give rise to an additional scattering, and hence the depth to which the light would penetrate would get reduced. If the particles are small in comparison with the wave-length, the scattering would still be proportional to λ^{-4}. If present in small quautities, there would be little effect on the characters of the returned light, but if present in larger quantities, there would be less chance for the absorptive properties of the medium to have their full play, and as a consequence, the light would be more mixed with the longer wave-lengths, and the blue colour of the sea would tend to get less saturated. As the particles get larger in comparison with the wave-length, the scattering in the direction of primary propagation will be specially favoured, and also, instead of being proportional to, it would tend to be independent of the wave-length. Since the light of longer wave-lengths can return by other means than molecular scattering, their relative proportion in the light returned would increase more and more as the quantity of suspended matter increased, and the sea would get greenish blue, green, whitish green, and finally white. However, as we shall see, when the quantity of matter is not large, the light scattered against the direction of the incident light is but an insignificant fraction of that scattered in the direction of the incident light.

* Lord Rayleigh, 'Scientific Papers,' vol. ii. table i. p. 503.

III. *Examination of Light scattered by Sea-water.*

Samples of sea-water were collected in carefully cleaned stoppered bottles from the Bay of Bengal in two voyages between Calcutta and Rangoon from places where the sea exhibited different colours varying from deep indigo to green. The bottles were securely placed in a galvanized-iron wire cage tied to the end of a wire, and the cage was thrown into the sea from the lower deck of the ship near the bow. The bottles were rinsed out with the sea-water five or six times before each sample was finally collected. The colour of the sea at the time was also noted. In observing the proper colour of the sea, a nicol is helpful in abolishing sky-reflexion, as has been pointed out by Raman.

The scattering of light by the different specimens was examined by concentrating a beam of sunlight at the centre of each bottle in a dark room. The back surfaces of the bottles were painted black, in order to be better able to see the tracks. Table II. gives the details regarding the scattering in different specimens. The intensities of the transversely scattered light given in the last column are expressed in terms of that in dust-free distilled water.

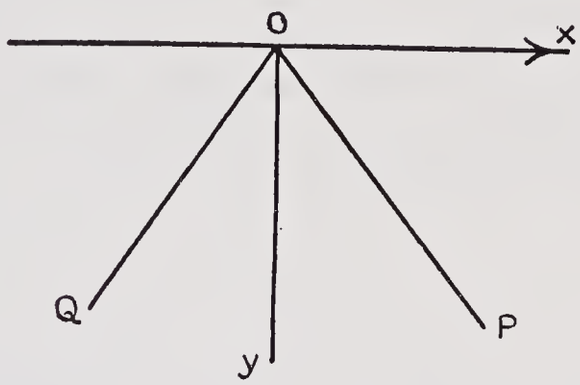
Table II.

Specimen No.	Date and time of collection.	Approximate position of ship at time of collection.	Colour of Sea.	Appearance of transversely scattered light.	Intensity of transversely scattered light.
A	1.10.22. 10.30 A.M.	...	Indigo.	Indigo with visible particles.	1·68
B	4.11.22. 8 A.M.	Lat. 19° 40′ N. Long. 90° E.	Greenish blue.	Blue—Few visible particles.	1·4
C	4.11.22. 11.15 A.M.	Lat. 19° 10′ N. Long. 90° 30′ E.	Deep blue.	Indigo—A few large particles.	1·5
D	4.11.22. 4 P.M.	Lat. 18° 30′ N. Long. 91° E.	Indigo.	Indigo—A few large particles.	1·5
E	5.11.22. 7.30 A.M	...	Greenish.	Blue with large thin flakes of something floating.	1·65
F	5.11.22. 11.40 A.M.	Lat. 15° 30′ N. Long. 94° 15′ E.	Green.	Bluish white—Motes visible.	1·6 Blue. 2·0 Red.

The colour of the transversely scattered light in specimens A, C, and D approached that of dust-free distilled water. The intensity of the transversely scattered light from A was compared with that from dust-free distilled water, by sending a concentrated beam of light through the two bottles in succession and making use of an Abney rotating disk-photometer for equalizing the intensities. Correction was made for the loss of light on reflexion at the glass surfaces. In the case of the other specimens, the comparisons were made by inserting perpendicularly in the path of the stronger beam a number of thin, selected microscope slides, so as to equalize the apparent brightnesses.

When the direction of observation was OP instead of Oy, the suspended particles were much more in evidence

Fig. 1.

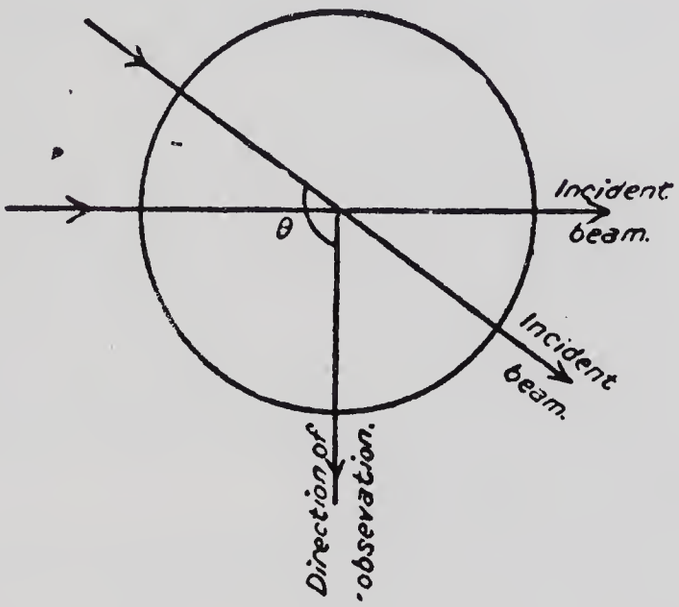


and the colour was more reddish. On the other hand, in the direction OQ, the particles were less conspicuous and the colour even more saturated than along Oy. This is what we should expect if the particles are large in comparison with the wave-length. Since, in the case of the sea, we are primarily concerned with the light proceeding backward, we should consider the intensity of the scattered beam in a direction against that of the incident beam. Comparisons of the intensity of scattering in different directions were made by the method indicated below (fig. 2).

Two beams of sunlight were concentrated one above the other at the centre of the bottle by two lenses of the same focal length (nearly 100 cm. and achromatic) in directions making a definite angle with each other. The scattering was observed in a direction at right angles to one of the beams, and the apertures of the lenses were adjusted by suitable shutters so that the tracks appeared of equal intensity. The inverse ratio of the areas of the apertures

gives the ratio of the intensities scattered in the two directions. Since the depth of layer contributing to the luminosity is different in the two cases, being proportional to cosec θ, where θ is the angle indicated in the figure, the

Fig. 2.



luminosity observed in the direction θ was multiplied by $\sin\theta$ in order to get the effect due to the same thickness of radiating column. Table III. gives the relative intensities of scattering in different directions in specimen A :—

TABLE III.

S_θ = Scattering in specimen in direction θ.

σ_θ = Scattering in dust-free distilled water in direction θ.

θ.	$S_\theta/S_{90°}$.	$S_\theta/\sigma_{90°}$.	$\sigma_\theta/\sigma_{90°}$.
30°	1·12	1·88	1·60
45°	0·91	1·53	1·40
60°	0·87	1·46	1·20
90°	1·00	1·68	1·00
120°	2·54	4·26	1·20
150°	5·5	9·2	1·60

The values in the fourth column are calculated on the assumption that the scattering by a pure, dust-free liquid in a direction θ is given by $\sigma\left(1+\frac{1-r}{1+r}\cos^2\theta\right)$, where σ is the scattering in a direction perpendicular to the incident beam. It will be seen that in the particular specimen of sea-water, when θ is greater than 90°, the scattering increases with

increasing values of θ at a much more rapid rate than in dust-free water, and that although the transverse scattering is 1·68 times that of dust-free water, the values of the scattering in directions 30° and 45° are not appreciably different from those of pure water. From the progress of values, we may expect that with smaller values of θ, the scattering will be practically the same as for dust-free water.

This result is of great importance in its bearing on the colour of the sea. Suspended matter, when present in small quantities, although it considerably increases the total scattering, contributes but little to the scattering against the direction of the incident light. The increase in the total scattering would reduce the transparency of the medium, but so long as the defect of transparency due to this cause is small compared with the absorption proper, the quality and intensity of the returned light would not be much affected by the presence of such matter.

Table IV. gives similar data for specimens B, C, and F. With a view to bringing out the difference in the distribution of scattered light for red and blue, comparisons were made after introducing ruby-red and deep-blue glasses respectively in the paths of the scattered beams.

TABLE IV.

θ.	$S_\theta/S_{90°}$.					
	B.		C.		F.	
	Red.	Blue.	Red.	Blue.	Red.	Blue.
30°	1·01	1·22	1·06	1·13	0·88	1·03
45°	1·10	1·05	1·13	1·13	0·95	1·02
60°	0·90	1·00	0·97	0·97	0·83	0·95
90°	1·00	1·00	1·00	1·00	1·60	1·00
120°	1·65	1·52	1·55	1·60	2·09	1·63
135°	3·92	2·45	3·18	2·76	5·05	3·98
150°	9·0	6·0	8·3	6·3	·16	9·4

It will be observed that in all cases the red gets more and more prominent as θ increases.

We shall now examine whether we can find in the varying amount of suspended matter a sufficient cause for the difference in the colour of the seas. For example, the specimen C was collected from a deep blue sea, while specimen B was from a sea which showed greenish blue,

and F from a place where the sea was green. Compared with C, the intensity of scattering in F, although nearly equal for the blue in a transverse direction, is greater by 30 per cent. in the red, and the asymmetry of scattering also is greater. Thus the total scattering of unit volume of specimen F is greater than that of C, and the colour is also much less blue. Both these causes would contribute to a less deep penetration of the light into the medium (relatively more so for longer wave-lengths), and thus the absorption would have less chance of playing its full role, so that the blue, indigo, and violet would be mixed up with a greater proportion of the longer wave-lengths. We should therefore expect the sea to be brighter and of a less saturated blue, but not the distinct green that it actually was. We have therefore to look for some other cause for the green colour. The point is even clearer if we compare the behaviour of B and C. B scatters actually less than C in a transverse direction (nearly 10 per cent. less); and although its track was not indigo like that of C, the asymmetry of scattering was of practically the same order of quantities, and yet the colour of the sea from which it was collected was *greenish blue*.

IV. *Fluorescence of Sea-Water.*

The reason for the difference was found on examining the transversely scattered light from a horizontal track for polarization by means of a double-image prism. When the double-image prism is so oriented as to transmit vertical and horizontal vibrations, the light corresponding to the horizontal vibrations does not actually vanish even in the case of dust-free distilled water * ; but in this case the two beams are of practically the same colour, while in the case of specimens B and F the weaker component was found to be distinctly greenish. The contrast came out sharper when the two beams were equalized for brightness by means of a suitably oriented nicol placed behind the double-image prism, and a double thickness of blue glass was introduced in the path of the incident beam. The green was now much brighter than the blue and the colour contrast sharper. This was evidently a case of *fluorescence*.

To make quite sure, the following arrangement was adopted:—In the path of the incident beam were placed a double thickness of cobalt-blue glass with an absorption cell.

* W. H. Martin, Journ. Phys. Chem. vol. xxiv. p. 478 (1920). C. V. Raman, 'Molecular Diffraction of Light,' chap. iv.

of a solution of potassium permanganate which cut off everything except the extreme blue and violet and a patch in the extreme red. The light was then passed through the sea-water, and the track therein was examined through a prism with its refracting edge horizontal. In addition to the blue and violet, the green was also conspicuously present. Yellow and red were present, but were very faint. Specimen F showed the effect best, B and E came next, and then C and D. The fluorescence was certainly present even in the last two specimens, though it was very weak.

Since the incident light did not contain any ultra-violet, the fluorescence should be excited by the blue and violet. This implies an extra absorption of the blue and the violet. A sea whose water shows the fluorescence would thus appear green, not only because there is a return of green light due to fluorescence, but also as there would be less of the blue and violet returning. As we have seen, that water looks most green which shows the most intense fluorescence, and the water gets more and more towards indigo as the fluorescent material gets less and less.

The transition from the indigo of the deep sea far from land to blue and green may thus be due either to the increase in the amount of suspended matter present, or to the presence of some fluorescent material (most probably organic) which not only causes a return of the green and longer wave-lengths, but also produces a greater absorption of the blue and the violet. The second cause is apparently the more important.

V. *Summary.*

The paper contains a discussion of Raman's theory of the colour of the sea with observations on the scattering of light by different specimens of sea-water from the Bay of Bengal.

(i.) It is shown that an ocean of pure dust-free water would, owing to the effects of molecular scattering and absorption, return light of an indigo-blue colour. The presence of *small* quantities of suspended matter would not appreciably affect the colour. With increasing quantities of suspended matter the colour would change to bluish, green, greenish white, and white.

(ii.) The transverse scattering from different specimens of sea-water has been compared with that of dust-free vacuum-distilled water. The water from the deep blue sea scatters light of nearly the same colour as dust-free water, and the intensity of the transversely scattered light is also of the same order.

(iii.) The intensity of scattering in different directions from different specimens of sea-water has been studied. The effect of dust is negligible so far as scattering against the direction of the incident light is concerned.

(iv). The variation of the dust-content is found to be insufficient to explain the changes of the colour of the sea from place to place. An important reason for the colour changes has been traced to the presence of varying amounts of some fluorescent material present in the sea. It is pointed out that this fluorescence also implies a greater absorption in the blue and violet involving a diminution of intensity at this end of the spectrum in the light returned from the sea.

In conclusion, I would express my most sincere thanks to Professor C. V. Raman for his stimulating interest in the work.

Rangoon,
Feb. 10, 1923.

I. Electromagnetic Theory of the Scattering of Light in Fluids.

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Contents.

1. Introduction.
2. Continuous Medium Theory.
3. Scattering by Isotropic Molecules.
4. Scattering by Anisotropic Molecules.
5. Comparison with Experiment.
6. Synopsis.

1. Introduction.

The subject of "Molecular Scattering of Light" whose foundations were laid by the late Lord Rayleigh, gained a new significance from the experimental work of Cabannes[1] and the present Lord Rayleigh[2] on the scattering of light in dust-free gases. Its importance was further increased by Prof. Raman's[3] application of Einstein's investigation of critical opalescence to the case of scattering in fluids in general, and his explanation of the blue of the sea as being caused by molecular scattering of light in water. Experimental work by the present author[4] on the

[1] Cabannes—Ann. Physique, Tome XV, 1920, pp. 1-150.

[2] Rayleigh—Proc. Roy. Soc. A, 1918, p. 453.

[3] C. V. Raman—Proc. Roy. Soc. A, April, 1922, p. 65 and, Molecular Diffraction of Light,' Calcutta University Press, 1922.

[4] K. R. Ramanathan—Proc. Roy. Soc. A., 1922, p. 151.

scattering of light in ether and by Mr. R. Venkateswaran [5] in normal pentane showed that throughout the range of temperatures from 35°C to the critical point, both in the saturated vapour state and in the liquid state in equilibrium with the vapour, the intensity of scattering in a transverse direction is given by the Einstein-Smoluchowski expression (with a correction for admixture with unpolarised light).

$$I = \frac{\pi^2}{18} \frac{RT\beta}{N\lambda^4 r^2} \quad (\mu^2-1)^2 \, (\mu^2+2)^2$$

where I is the intensity of the scattered light from a unit volume at a large distance r from the volume.

R, N are the gas-constant and the number of molecules respectively per gram-molecule

T is the absolute temperature

β is the isothermal compressibility of the medium

μ is its refractive index, and

λ is the wave-length of the incident light.

The above expression was derived by Einstein on the assumption that the scattering of light was caused by the local changes in dielectric displacement consequent upon the local fluctuations of density to which an otherwise uniform medium is subject owing to the thermal movements of its parts. In such a case, the light scattered in a direction transverse to the primary beam should be completely polarised. The same result may be deduced when the individual molecules are regarded as sources of scattered radiation provided that they are supposed to be spherically symmetrical and their restricted freedom of movement is taken into account. Actually, however, the transversely scattered light is in general found to be imperfectly polarised, much more so in a liquid than in its vapour. The imperfect polarisation has been explained

[5] R. Venkateswaran—Trans. Chem. Soc., 1922, Vol. 121, p. 2655.

by the late Lord Rayleigh,[6] Born[7] and Gans[8] on the assumption of molecular anisotropy. The subject has also been studied by Sir J. J. Thomson[9] from the point of view of the electron theory. The increase of imperfection of polarisation in the liquid state is remarkable and an explanation of it has been given by Raman on the idea that the scattering in a fluid can be considered to be made up of two parts, a density-scattering and an orientation-scattering of which the former is given by the Einstein-Smoluchowski formula while the latter is proportional to the density of molecules. It is obviously of importance to make an exact investigation of the connection between the state of aggregation of a medium and the quality of the scattered light, especially in view of the fact that it promises to throw light on the nature of the liquid state itself. In the following paper, an attempt is made to develop a general theory of scattering in fluids. In Article 2, the medium is assumed to be continuous as in Einstein's treatment of the subject, but subject to local fluctuations of density depending upon the laws of statistical mechanics. Lorentz's electromagnetic treatment of the scattering of light in gases developed in his book "Les Theories Statistique en Thermodynamique" has been adopted and extended to the general case of a fluid of any compressibility. In Article 3, the subject is treated from the molecular standpoint in the case when the molecules are isotropic and the Einstein-Smoluchowski formula for scattering is deduced. In Article 4, the molecular treatment is extended to the case when the molecules are anisotropic and expressions are deduced for the intensity of the scattered light, its state of polarisation and the co-efficient of extinction in the medium. In

[6] Rayleigh—Phil. Mag, XXX, 1918, and Scientific Papers, Vol. VI, p. 540.

[7] Born—Verh. Deutsch. Phys. Gesell., Vol. 19, p. 243, 1917, and Vol. 20, p. 16, 1918.

[8] Gans—Ann. der Physik—10, 1931.

[9] Sir J. J. Thomson—Phil. Mag., XL, 1920, p. 393.

Article 5, the results are discussed with reference to experimental data as regards polarisation of the scattered light in liquids and their vapours. Article 6 contains a synopsis of the principal results of the investigation.

2. "Continuous Medium" Theory.

Let K_o be the value of the dielectric constant when there is a uniform distribution of matter and $K_o+\delta K$ its actual value at a volume element δv.

In any actual fluid, owing to thermal movements, the density at any point undergoes incessant fluctuations and hence the dielectric constant also.

Using Heaviside units, the dielectric displacement $D=K_oE$ (1) where E is the electric intensity. When the density and consequently the dielectric constant are uniform, there would be no scattering, for the disturbances from different elements of volume would mutually cancel each other, except in the direction of primary propagation.

At a place where the dielectric constant is $K_o+\delta K$,

$$D_1=(K_o+\delta K)\,E \qquad (2)$$

Here, there is a discontinuity of displacement which could be annulled by introducing a supplementary electric intensity

$$F=-\frac{\delta K}{K_o}E \qquad (3)$$

For, then

D_1 would become $(K_o+\delta K)(E-\frac{\delta K}{K_o}E)$ which is equal to K_oE if we neglect $(\delta K/K_o)^2$ in comparison with unity. As matters actually are, the scattering is identical with the radiation due to a system of electric intensities $-F$ or $\frac{\delta K}{K_o}E$ at the places where the dielectric constant differs from its mean value K_o by δK.

Suppose we have a volume element δv at the origin of co-ordinates at which the dielectric constant is $K_o+\delta K$. When the linear dimensions of the element are small in comparison with the wave-length, the amplitude of the disturbance from the element would be proportional to $\frac{\delta K}{K_o}E\delta v$ and hence its energy proportional to

$$\left(\frac{\delta K}{K_o}\right)^2E^2(\delta v)^2 \qquad (4)$$

As a first step, then, we have to calculate the radiation caused by an extraneous periodic intensity acting throughout a volume element δv at a given point in a homogeneous isotropic dielectric. The problem is analogous to that solved by Hertz in the case of the vibrating electric doublet.

Let E represent the electric intensity

H „ magnetic „

D „ dielectric displacement

and F the extraneous electric intensity acting throughout the element of volume δv.

We shall take the magnetic permeability of the medium to be unity.

The field equations are

$$\left.\begin{aligned} \text{Curl } H &= \frac{1}{c}\frac{\partial D}{\partial t} \\ \text{Curl } E &= -\frac{1}{c}\frac{\partial H}{\partial t} \end{aligned}\right\} \tag{5}$$

where c is the velocity of light in vacuo

Also
$$D = K(E+F) \tag{6}$$

and
$$\left.\begin{aligned} \text{div } H &= o \\ \text{div } D &= o \end{aligned}\right\} \tag{7}$$

Eliminating H from (5) and making use of (6), we get

$$\nabla^2 E - \frac{K}{c^2}\frac{\partial^2 E}{\partial t^2} = \frac{K}{c^2}\frac{\partial^2 F}{\partial t^2} + \text{grad div } E \tag{8}$$

To solve (8), following Lorentz,[10] we shall introduce a new vector A given by

$$\nabla^2 A - \frac{K}{c^2}\frac{\partial^2 A}{\partial t^2} = -F \tag{9}$$

In order that (8) and (9) may simultaneously be true,

$$E = \text{grad div } A - \frac{K}{c^2}\frac{\partial^2 A}{\partial t^2}. \tag{10}$$

and

$$H = \frac{K}{c}\frac{\partial}{\partial t}[\text{curl } A] \tag{11}$$

Equation (9) is of a well-known form and its solution is

$$A = \frac{1}{4\pi}\int \frac{1}{r} F_{\left(t-\frac{r}{v}\right)} dv \tag{12}$$

[10] H. A. Lorentz—Les Theories Statistique en Thermodynamique, pp. 42-43.

where the integration is taken over the whole space in which F differs from zero and where $u = \frac{c}{\sqrt{K}}$ is the velocity of electromagnetic waves in the medium, r is the distance from dv of the point at which A is required and $F_{\left(t-\frac{r}{u}\right)}$ is the value of F at time $t-\frac{r}{u}$

When F is a periodic electric intensity $F_o \cos pt$ in the direction of the z-axis, confined to a single volume element δv at the origin of co-ordinates.

$F_x = o, \quad F_y = o \quad$ and $\quad F_z = F_o \cos pt$

Hence from (12)

$$A_x = 0, \qquad A_y = 0, \qquad A_z = \frac{F_o \delta v}{4\pi r} \cos p\left(t-\frac{r}{u}\right)$$

From (10),

$$E_x = \frac{\partial^2 A_z}{\partial z \partial x}, \; E_y = \frac{\partial^2 A_z}{\partial y \partial z} \text{ and } E_z = \frac{\partial^2 A_z}{\partial z^2} - \frac{1}{u^2}\frac{\partial^2 A_z}{\partial t^2}$$

The magnetic intensities, can, if necessary, be easily deduced from (11). For distances from the origin large in comparison with the wave-length, $\frac{1}{r^2}$ and $\frac{1}{r^3}$ can be neglected in comparison with $\frac{1}{r}$ and hence

$$E_x = -\frac{xz}{r^3}\omega, \; E_y = -\frac{yz}{r^3}\omega, \text{ and } E_z = \left(\frac{1}{r} - \frac{z^2}{r^3}\right)\omega \qquad (13)$$

where $\omega = \frac{p^2 F_o \delta v}{4\pi u^2} \cos p\left(t-\frac{r}{u}\right)$

The intensity of the radiation would be proportional to $E_x^2 + E_y^2 + E_z^2$ which is given by

$$\frac{x^2+y^2}{r^4}\omega^2 = \frac{\sin^2\theta}{r^2}\omega^2 \qquad (14)$$

where θ is the angle between the direction of the ray and the axis of z (the direction of the applied electric intensity).

In the case of scattering by a single volume element δv,

$F_o = -\frac{\delta K}{K_o} E$ and the ratio of $E_x^2 + E_y^2 + E_z^2$ to E^2 the square of the amplitude of the incident wave is given by

$$\frac{\sin^2\theta}{r^2}\left(\frac{2\pi}{\lambda_1}\right)^4\left(\frac{\delta K}{K_o}\right)^2\frac{\delta v^2}{16\pi^2} \qquad (15)$$

where $2\pi/\lambda_1$ has been substituted for p/u. λ_1 is the wave-length of the incident vibration in the medium.

Let us now consider the scattering produced by the accidental deviations of density in an extended volume. Let us take the X-axis to be the direction of the primary beam. The density deviations would change both in magnitude as well as in position in a perfectly arbitrary manner and there would be no co-ordination of phase between the vibrations scattered by the various elements. As a consequence, over any finite time-interval, the energies and not the amplitudes of the scattered radiations from the different elements of volume would be additive. If $\delta\rho$ denotes the deviation of density from its uniform value ρ_o in a volume element δv then we can easily show[11] by applying Boltzmann's principle of entropy-probability that the mean square of deviation of density is given by

$$\overline{(\delta\rho^2)} = \frac{R\,T\beta}{N\delta v}\rho_0^2 \qquad (16)$$

The relation between density and dielectric constant is given by Lorentz's equation

$$\frac{K_0-1}{(K_0+2)\,\rho_0} = \text{constant.}$$

$$\text{Hence } \frac{\partial K}{\partial \rho} = \frac{(K_0-1)\,(K_0+2)}{3\rho_0}$$

and

$$\delta K = \frac{\partial K}{\partial \rho}\delta\rho$$

$$\overline{\delta K^2} = \frac{(K_0-1)^2(K_0+2)^2}{9\rho_0^2}\overline{\delta\rho^2}$$

$$= \frac{(K_0-1)^2\,(K_0+2)^2}{9}\,\frac{RT\beta}{N\delta v}$$

Substituting in (15) $\overline{\delta K^2}$ for δK^2 we get for the ratio of the average intensity of the scattered radiation to that of the incident

$$\frac{\pi^2}{9}\,\frac{RT\beta}{NK^2\lambda_1^4}\,(K_0-1)^2\,(K_0+2)^2\,\frac{\sin^2\theta}{r^2}\,\delta v$$

and since the radiations from different volume elements are additive

$$\frac{\pi^2}{9}\,\frac{RT\beta}{N\lambda^4}\,(K_0-1)^2\,(K_0+2)^2\,\frac{\sin^2\theta}{r^2}\ \text{per unit volume} \qquad (17)$$

[11] Einstein—Ann. der Physik, Vol. 1910, p. 1275, also C. V. Raman and K. R. Ramanathan—Phil. Mag., Jan. 1923.

where λ is the wave-length of the incident vibration in vacuo. The radiation in the direction of the z axis is zero and is a maximum in the xy plane.

When the incident light is unpolarised, the ratio of the intensity of the light scattered in a transverse direction to the intensity of the incident beam is given by

$$\frac{\pi^2}{18}\frac{RT\beta}{N\lambda^4}(K_0-1)^2(K_0+2)^2\frac{1}{r^2}$$

In a direction making an angle ϕ with the incident beam, this becomes

$$\frac{\pi^2}{18}\frac{RT\beta}{N\lambda^4}(K_0-1)^2(K_0+2)^2\left\{\frac{1+\cos^2\phi}{r^2}\right\} \qquad (18)$$

To get the extinction co-efficient, we have only to find the total scattering from a stratum of thickness dx and unit area of cross-section. Integrating (18) over the surface of a sphere of radius r, the ratio of the energy scattered by such a stratum to the incident energy is given by

$$\frac{dI}{I_0}=\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}(K_0-1)^2(K_0+2)^2 dx$$

$$\therefore I=I_0 e^{-hx}$$

$$\text{where } h=\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}(K_0-1)^2(K_0+2)^2$$

We might substitute μ^2 for K_0 in the above expressions where μ is the refractive index of the medium for the particular frequency.

3. *Scattering by Isotropic Molecules.*

Considering the problem from a molecular standpoint, the effect of an incident electromagnetic wave on the molecules of a medium is to produce a displacement of the electrons in the molecules which is equivalent to creating an oscillating electric doublet in each 'molecule

with a period the same as that of the wave. When the molecules are isotropic, the axes of the doublets coincide in direction with that of electric intensity, but when they are anisotropic, the displacements of the electrons are not in general in that direction, but the effect may approximately be taken to be equivalent to creating three doublets with their axes along three principal directions in each molecule. The field to which any molecule is subject is the resultant of that due to the incident wave and that due to the polarisation of the neighbouring molecules. The latter is taken account of in Lorentz's well known treatment of dispersion in homogeneous, isotropic media. In the case of a gas at atmospheric pressure, its effect is negligible. The treatments of the scattering of light by isotropic molecules by the late Lord Rayleigh, Natanson, Sir J. J. Thomson and others do not take into account the influence of the surrounding molecules. Einstein's treatment of the subject does consider the effect due to the polarisation of the surrounding dielectric, but the treatment is non-molecular, and the results apply only to the case of a medium composed of isotropic molecules. With a view to extension to the case when the molecules are anisotropic, a molecular treatment of the problem is given below, taking into account the effect of the neighbouring molecules.

Consider a plane polarised wave travelling in the direction Ox. Let Z be the electric intensity in the wave parallel to Oz and proportional to $\cos pt$. Under the influence of the wave, each molecule becomes equivalent to a doublet with its axis parallel to Oz. Let A be the moment induced in a molecule when it is placed in a field of unit intensity. If the medium be of uniform density and if n_0 denotes the number of molecules per unit volume and M_0 the electric moment of each doublet,

2

the actual intensity at any point O in the medium is given by

$$Z+\frac{4\pi}{3}n_0M_0$$

and

$$M_0=A\left(Z+\frac{4\pi}{3}n_0M_0\right)$$

$$=AZ\Big/\left(1-\frac{4\pi}{3}n_0A\right) \tag{19}$$

Now K_0 the square of the refractive index of the medium for waves of frequency $p/2\pi$ is given by

$$\frac{K_0-1}{K_0+2}=\frac{4\pi}{3}n_0A \tag{20}$$

and hence

$$M_0=AZ\frac{(K_0+2)}{3} \tag{21}$$

A vibrating electric doublet radiates out energy. According to Hertz's well known solution, the electric intensity at time t at a point r distant (great in comparison with λ) from the doublet is

$$\frac{p^2M_{0\ t-\frac{r}{c}}}{c^2r}\sin\theta \tag{22}$$

where c is the velocity of light in vacuo, θ is the angle between Oz and the direction of the ray and $M_{0\ (t-\frac{r}{c})}$ stands for the value of the moment at time $t-\frac{r}{c}$.

When the molecules of the medium are uniformly distributed and we consider the effect due to a volume whose dimensions are large compared with λ, it vanishes in all directions except in the direction of primary propagation where the secondary waves from the different molecules in the wave-front combine with the original wave and give rise to a plane wave moving with an altered velocity. In any actual fluid medium, however, owing to the thermal movements of the molecules, and the consequent fluctuations of density at any point, there

is a finite radiation of energy in all directions. If n_o represents the average number of molecules per unit volume in a volume element δv and $\overline{\delta n^2}$ the mean square of the deviations of that number, then as before

$$\frac{\overline{\delta n^2}}{n_0^2} = \frac{RT\beta}{N\delta v} \tag{23}$$

Consider a volume element δv at O small in comparison with a cubic wave-length, but large compared to the dimensions of a molecule. Let n be the number of molecules per unit volume in δv and let n be equal to $n_0 + \delta n$. The electric intensity at P due to scattering by the molecules contained in δv would be given by

$$\frac{p^2}{c^2 r} \sin\theta\, \delta v\, (Mn - Mn_o) \tag{24}$$

where M is the electrical moment appropriate to the density n.
When we are considering the average effect over finite intervals of time, the distinction between M and $M_{(t-\frac{r}{c})}$ may be dropped. Now

$$= \frac{p^2}{c^2 r} \sin\theta \left[(M_o + \delta M)(n_o + \delta n) - M_o n_o \right] \delta v \tag{24}$$

$$= \frac{p^2}{c^2 r} \sin\theta\, (M_o \delta n + n_o \delta M)\delta v \tag{25}$$

Now, differentiating (19) and applying (20)

$$\delta M = \frac{(K_o - 1)(K_o + 2)}{9} AZ \frac{\delta n}{n_o}.$$

$$\therefore\ n_o \delta M + M_o \delta n = \left(\frac{K_o + 2}{3}\right)^2 AZ\delta n$$

$$= \frac{(K_o - 1)(K_o + 2)}{12\pi} Z \frac{\delta n}{n_o} \tag{26}$$

Let us consider the effect due to (25). If E is the electric intensity at P due to radiation from δv, the energy is proportional to E^2. It is thus

$$\frac{p^4 \sin^2\theta}{c^4 r^2} (M_o \delta n + n_o \delta M)^2\, \delta v^2$$

$$= \frac{p^4 \sin^2\theta}{c^4 r^2} \frac{(K_o - 1)^2 (K_o + 2)^2}{144\pi^2} Z^2 \frac{\delta n^2}{n_o^2}\, \delta v^2$$

Since δn varies from instant to instant according to the laws of chance the average expectation of E^2 over a sufficiently long interval of time is

$$\overline{E^2} = \frac{p^4 \sin^2\theta}{c^4 r^2} \frac{(K_0-1)^2(K_0+2)^2}{144\pi^2} Z^2 \frac{\overline{\delta n^2}}{n_0^2} \delta v^2$$

By (23),

$$\overline{E^2} = \frac{p^4 \sin^2\theta}{c^4 r^2} \frac{(K_0-1)^2(K_0+2)^2}{144\pi^2} Z^2 \frac{RT\beta}{N} \delta v$$

When we consider the effect due to a volume V whose dimensions are large in comparison with λ, the ratio of the square of the electric vector in the scattered radiation to that in the incident is

$$\frac{\overline{E^2}}{Z^2} = \frac{p^4 \sin^2\theta}{c^4 r^2} \frac{(K_0-1)^2(K_0+2)^2}{144\pi^2} \frac{RT\beta}{N} V.$$

$$= \frac{\pi^2}{9} \frac{RT\beta}{N\lambda^4} (K_0-1)^2(K_0+2)^2 V. \quad \frac{\sin^2\theta}{r^2}$$

where λ is the wave-length of the light in vacuo.

4. *Scattering by Anisotropic Molecules.*

Let $O'\xi$, $O'\eta$, $O'\zeta$ denote the three principal directions in a molecule whose centre is O'.

Let A, B, C be the moments induced in the molecule when placed in a field of unit intensity parallel to $O'\xi$, $O'\eta$, $O'\zeta$ respectively.

As before, let Oz be the direction of the incident polarised plane wave and Z the electric intensity along Oz. In a medium composed of isotropic molecules the axis of the induced doublet in each molecule would be parallel to Z; there would be no component along Oz or Oy. In a medium composed of anisotropic molecules, however, there would, in general, be components both along the x and the y axes. But when the axes of the molecules are oriented *at random* the components of the induced moments along the x and y directions would be as much positive as negative and hence the polarisation fields parallel to the x and y axis which may be taken as $\frac{4}{3}\pi n_0 \overline{M_x}$ and $\frac{4}{3}\pi n_0 \overline{M_y}$ respectively would vanish. We would however still have $\frac{4}{3}\pi n_0 \overline{M_z}$ because M_z can have only positive values. The effect of the polarisation of the surrounding

molecules is then to produce an additional field of $\frac{4}{3}\pi n_0 \overline{M_z}$. The resultant electric field at a point in the medium is therefore

$$Z + \frac{4}{3}\pi n_0 \overline{M_z} \tag{27}$$

To calculate $\overline{M_z}$, we note that if the molecules are oriented at random,

$$\overline{M_z} = \frac{A+B+C}{3}\left[Z + \frac{4}{3}\pi n_0 \overline{M_z}\right]$$

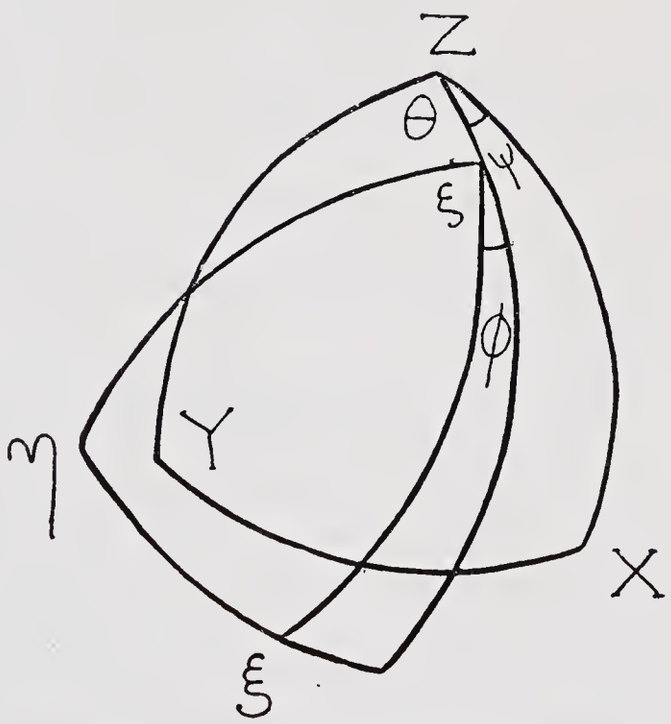
$$= \frac{A+B+C}{3} Z \cdot \frac{K_0+2}{3}$$

and

$$\frac{K_0-1}{K_0+2} = \frac{4\pi n_0}{3}\left[\frac{A+B+C}{3}\right] \tag{28}$$

Consider a molecule, the direction of whose principal axes is defined by the Eulerian angles θ, ϕ, ψ.[1]

In figure 1, x, y, z represent the points where $O'x$, $O'y$, $O'z$ cut a sphere of unit radius, and ξ, η, ζ the points where the axes of the molecule cut the same sphere.



The moments induced in the molecule parallel to $O'\xi$, $O'\eta$, $O'\zeta$ are

$$-AZ\left(\frac{K_0+2}{3}\right)\sin\theta\cos\phi$$

$$BZ\left(\frac{K_0+2}{3}\right)\sin\theta\sin\phi \tag{29}$$

$$CZ\left(\frac{K_0+2}{3}\right)\cos\theta$$

[1] Lord Rayleigh and Sir J. J. Thomson, *loc. cit.*

When these are resolved along Ox, Oy, Oz the components are

$$M_x = Z\left(\frac{K_o+2}{3}\right)\left[\sin\theta\cos\theta\cos\psi\,(C-A\cos^2\phi-B\sin^2\phi)\right.$$
$$\left.+(A-B)\sin\theta\sin\psi\sin\phi\cos\phi\right]$$

$$M_y = Z\left(\frac{K_o+2}{3}\right)\left[\sin\theta\cos\theta\sin\psi\,(C-A\cos^2\phi-B\sin^2\phi)\right.$$
$$\left.+(A-B)\sin\theta\cos\psi\sin\phi\cos\phi\right]$$

$$M_z = Z\left(\frac{K_o+2}{3}\right)\left[C\cos^2\theta + B\sin^2\theta\sin^2\phi + A\sin^2\theta\cos^2\phi\right] \quad (30)$$

which, for shortness, we may write

$$Z\left(\frac{K_o+2}{3}\right)L_1, \qquad Z\left(\frac{K_o+2}{3}\right)L_2, \qquad Z\left(\frac{K_o+2}{3}\right)L_3$$

The mean value of M_x and M_y taken over all orientations is zero, while that of M_z is $Z\left(\frac{K_o+2}{3}\right)\left(\frac{A+B+C}{3}\right)$. At a point on the y-axis distant r from O, the square of the x-component of the electric intensity due to scattering from a molecule at O is

$$\frac{p^4}{c^4r^2}M_x^2$$

and from the molecules contained in a volume element δv the average expectation of X'^2 is

$$\overline{X'^2} = \frac{p^4}{c^4r^2}\,\overline{M_x^2}\,n\delta v$$

Since M_x has positive and negative values equally often at random, $\overline{X'^2}$ *is proportional to the number of molecules.*

Averaged over all orientations of molecules

$$\overline{X'^2} = \frac{p^4}{c^4r^2}Z^2\left(\frac{K_o+2}{3}\right)^2\frac{1}{15}(A^2+B^2+C^2-AB-BC-CA)n_o\delta v$$

$$= \frac{p^4}{c^4r^2}Z^2\left(\frac{K_o+2}{3}\right)^2 f\,n_o\delta v$$

where

$$f = \frac{1}{15}(A^2+B^2+C^2-AB-BC-CA)$$

and from a volume V

$$\overline{X'^2} = \frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_o+2}{3}\right)^2 f n_o V \qquad (31)$$

In the case of the Z-component, we note that it can have only values of the same sign as Z. Hence from a *small* volume element δv, the amplitudes of the electric forces are additive. The Z-component of the electric force due to a single molecule at 0 is given by

$$\frac{p^2}{c^2 r} M_z$$

and from the $n\delta v$ molecules contained in the volume element δv

$$Z' = \frac{p^2}{c^2 r} M_z n \delta v$$

$$= \frac{p^2}{c^2 r} (\overline{M}_z + \delta M_z)(n_0 + \delta n)\delta v$$

$$= \frac{p^2}{c^2 r} (\overline{M}_z n_0 + \overline{M}_z \delta n + n_0 \delta \overline{M}_z)\delta v$$

The amplitude due to the first term cancels when the effect is taken over a finite volume and as in the case of isotropic molecules, we are left with the second and third terms

$$\therefore \quad Z'^2 = \frac{p^4}{c^4 r^2} (\overline{M}_z \delta n + n_0 \overline{\delta M_z})^2 \delta v^2$$

$$= \frac{p^4}{c^4 r^2} Z^2 \left(\frac{K+2}{3}\right)^4 \overline{L_3^2}\, \delta v^2\, \overline{\delta n^2}$$

as in (26).

The mean value of L_3^2 taken over all orientations is

$$g = \tfrac{1}{15}(3A^2 + 3B^2 + 3C^2 + 2AB + 2BC + 2CA)$$

$$\therefore \overline{Z'^2} = \frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_0+2}{3}\right)^4 \overline{\delta n^2}\, \delta v^2 \cdot g$$

aud by (23)

$$= \frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_0+2}{3}\right)^4 \frac{RT\beta}{N} \delta v . n_0^2 . g$$

and from a volume V, the same quantity

$$= \frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_0+2}{3}\right)^4 \frac{RT\beta}{N} n_0^2 g V \tag{32}$$

and

$$\frac{\overline{X^{12}}}{\overline{Z^{12}}} = \frac{f}{\left(\frac{K_0+2}{3}\right)^2 \frac{RT\beta}{N} n_0 g} = \frac{f}{\gamma g} \tag{33}$$

where

$$\gamma = \left(\frac{K_0+2}{3}\right)^2 \frac{RT\beta}{N} n_0 . \tag{34}$$

When the incident light is unpolarised, the ratio of the weak component to the strong in a direction perpendicular to the incident beam is

$$\frac{2f}{f+\gamma g} \tag{35}$$

For a gas at ordinary pressure obeying Boyle's law, this becomes

$$\frac{2f}{f+g} \tag{36}$$

in accordance with Rayleigh's result.

The total intensity of the scattered light from a unit volume in a direction perpendicular to the incident beam is

$$\frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_0+2}{3}\right)^2 \{3f n_0 + \gamma g n_0\} \tag{37}$$

To connect g and f with experimentally determinable quantities, we note that

$$f=\tfrac{1}{15}(A^2+B^2+C^2-AB-BC-CA)$$

$$g=\tfrac{1}{15}(3A^2+3B^2+3C^2+2AB+2BC+2CA)$$

$$\therefore \quad g-\tfrac{4}{3}f=\tfrac{1}{9}(A+B+C)^2$$

$$= \frac{9}{16\pi^2 n_0^2}\frac{(K_0-1)^2}{(K_0+2)^2} \tag{38}$$

and from (36) in the case of rare vapour for which Boyle's law holds good, the ratio of the weak component to the strong in the transversely scattered light is

$$r_1= \frac{2f}{f+g} \quad \therefore \quad f= \frac{3r_1(g-\frac{4}{3}f)}{6-7r_1} \tag{39}$$

The quantity under the brackets in (37) can be written

$$fn_0(3+\tfrac{4}{3}\gamma)+(g-\tfrac{4}{3}f)n_0\gamma$$

By (39), this reduces to

$$n_0(g-\tfrac{4}{3}f)\left\{\gamma+\frac{r_1(9+4\gamma)}{6-7r_1}\right\}$$

and (37) becomes

$$\frac{p^4}{c^4r^2}Z^2\left(\frac{K_0+2}{3}\right)^2 n_0(g-\tfrac{4}{3}f)\left\{\gamma+\frac{r_1(9+4\gamma)}{6-7r_1}\right\}$$

substituting the values of γ and $g-\frac{4}{3}f$ it reduces to

$$\frac{\pi^2 RT\beta}{9N\lambda^4}\frac{Z^2}{r^2}(K_0-1)^2(K_0+2)^2+\frac{Z^2}{r^2}\frac{\pi^2}{n_0\lambda^4}(K_0-1)^2\frac{r_1(9+4\gamma)}{6-7r_1}$$

Since the square of the electric intensity in the incident unpolarised light is $Y^2+Z^2=2Z^2=I_0$ say, this becomes

$$\frac{I_0}{r^2}\left\{\frac{\pi^2}{18}\frac{RT\beta}{N\lambda^4}\cdot(K_0-1)^2(K_0+2)^2+\frac{\pi^2}{2n_0\lambda^4}(K_0-1)^2\frac{r_1(9-4\gamma)}{6-7r_1}\right. \tag{40}$$

When A=B=C, that is, when the molecules are isotropic, $f=0$ and the expression reduces to the Einstein Smoluchowski formula

$$\frac{I_0}{r^2}\ \frac{\pi^2}{18}\ \frac{RT\beta}{N\lambda^4}\ (K_0-1)^2(K_0+2)^2$$

In the case of a vapour obeying Boyle's law, the expression becomes

$$\frac{I_0}{r^2}\ \frac{\pi^2}{2n_0\lambda^4}\ (K_0-1)^2\left\{1+\frac{13r_1}{6-7r_1}\right\}$$

The quantity outside the square brackets is the Rayleigh expression for scattering in gases obeying Boyle's law and the multiplying factor is the same as that introduced by Cabannes.

To obtain the co-efficient of extinction, we shall first find an expression for the total radiation from a unit volume when the incident light is polarised with its electric vector along the z axis. The squares of the components of the electric intensity in the light scattered from unit volume, in directions perpendicular to Ox, Oy, Oz are (31) and (32)

$$\overline{X^{12}}=\overline{Y^{12}}=\frac{p^4}{c^4r^2}Z^2\left(\frac{K_0+2}{3}\right)^2 fn_0$$

and

$$Z'^2=\frac{p^4}{c^4r^2}Z^2\left(\frac{K_0+2}{3}\right)^4\frac{RT\beta}{N}n_0^2y$$

$$=\frac{p^4}{c^4r^2}\cdot Z^2\left(\frac{K_0+2}{3}\right)^2\gamma y\ n_0.$$

This can be looked upon as a mixture of unpolarised light equal to $\frac{p^4}{c^4r^2}Z^2\left(\frac{K_0+2}{3}\right)^2 2f\,n_0$ and of polarised light

equal to $\frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_0+2}{3} \right)^2 n_0 (\gamma g - f)$ with the vibrations parallel to the z-axis. Integrating over the surface of a surface of a sphere of radius r, the total radiation becomes

$$\frac{p^4}{c^4} Z^2 \left(\frac{K_0+2}{3} \right)^2 n_0 \left[8\pi f + \frac{8\pi}{3} (\gamma g - f) \right]$$

$$= \frac{128\pi^5}{3\lambda^4} Z^2 \left(\frac{K_0+2}{3} \right)^2 n_0 (2f + \gamma g)$$

Putting in the values of f, g and γ, this becomes

$$Z^2 \left\{ \frac{8\pi^3}{27} \frac{RT\beta}{N\lambda^4} (K_0-1)^2 (K_0+2)^2 + \frac{8\pi^3}{3n_0\lambda^4} (K_0-1)^2 \frac{6r_1}{6-7r_1} \left(1+\frac{2\gamma}{3} \right) \right\}$$

and the fraction of the incident radiation scattered is

$$\frac{8\pi^3}{27} \frac{RT\beta}{N\lambda^4} (K_0-1)^2 (K_0+2)^2 + \frac{8\pi^3}{3} \cdot \frac{(K_0-1)^2}{n_0\lambda^4} \frac{6r_1}{6-7r_1} \left(1+\frac{2}{3}\gamma \right) \quad \ldots \quad (41)$$

Even if the incident light is unpolarised, the same expression holds good. For a gas obeying Boyle's law, this reduces to

$$\frac{8\pi^3}{3} \frac{(K_0-1)^2}{n_0\lambda^4} \left\{ \frac{6+3r_1}{6-7r_1} \right\} \quad \ldots \quad \ldots \quad \ldots \quad (42)$$

We can easily see that with unpolarised light, since the intensity of the light scattered along the y and z-axis is each

$$\frac{p^4}{c^4 r^2} Z^2 \left(\frac{K_0+2}{3} \right)^2 n_0 (3f + \gamma g)$$

and that along the x-axis is

$$\frac{p^4}{\epsilon^4 r^2} Z^2 \left(\frac{K_0+2}{3} \right)^2 n_0 (2f+2\gamma g)$$

the distribution of intensity is given by

$$\frac{8\pi^4}{\lambda^4} \cdot \frac{I_0}{r^2} \left(\frac{K_0+2}{3} \right)^2 n_0 \{(3f+\gamma g)+(\gamma g-f) \cos^2\phi\}$$

where ϕ is the angle between the directions of the incident and scattered beams.

When the values of f, g and γ are substituted this becomes

$$\frac{I_0}{r^2} \left[\frac{\pi^2}{18} \frac{RT\beta}{N\lambda^4} \cdot (K_0-1)^2 (K_0+2)^2 (1+\cos^2\phi) \right.$$

$$\left. + \frac{\pi^2}{2} \frac{(K_0-1)^2}{n_0\lambda^4} \frac{r_1}{6-7r_1} \{(9+4\gamma)+(4\gamma-3) \cos^2\phi\} \right]$$

$$= \frac{I_0}{r^2} \left[\frac{\pi^2}{18} \frac{RT\beta}{N\lambda^4} \cdot (K_0-1)^2 (K_0+2)^2 (1+\cos^2\phi) \right.$$

$$+ \frac{\pi^2}{2} \cdot \frac{(K_0-1)^2}{n_0\lambda^4} \frac{r_1}{6-7r_1} (4\gamma-3)(1+\cos^2\phi)$$

$$\left. + 12 \cdot \frac{\pi^2}{2} \cdot \frac{(K_0-1)^2}{n_0\lambda^4} \cdot \frac{r_1}{6-7r_1} \right]$$

5. *Comparison with Experiment.*

We shall calculate the imperfection of polarisation of the transversely scattered light in a number of liquids from (35) and (36) from the corresponding values for their vapours, and compare the results with the values obtained experimentally. For this, we shall use the data

obtained by Rayleigh[1] and by Raman and Seshagiri Rao.[2] The following table summarises the results.

Substance.	Weak Component / Strong Component (per cent).		
	Vapour.	Liqu d at 3 °c (Calc.).	Liquid at 30°c (obs.).
Ether	1·7	20	8·3
Benzene	6·5	75	39·8
CS_2	12·0	75	70
$CHCl_3$	3·0	31	15
CCl_4	3·1	49	11

The calculated values are uniformly too high. This seems to show that the *hypothesis of random orientations of molecules in liquids, which we have assumed in the development of the theory does not hold good.*

6. *Synopsis.*

1. An electromagnetic theory of the scattering of light in fluids has been worked out without assuming a molecular structure on the basis of Lorentz's treatment of the scattering of light in gases and the Einstein-Smoluchowski formula for scattering derived.

2. The same result is shown to follow if the fluid medium be supposed to be composed of isotropic molecules.

3. The treatment is extended to the case when the molecules are anisotropic in which case it is shown that if the orientations of the molecules are entirely at random, the transversely scattered light is imperfectly polarised, the ratio of the weak component to the strong being

[1] Rayleigh : Proc. Roy Soc. A, loc cit.

[2] C V. Raman and K. Seshagiri Rao: Phil. Mag vol. 45, 1923, p. 625 and "Molecular Diffraction of Light"

given by

$$r_1 = \frac{2f}{f+\gamma g}$$

where $\gamma = \left(\frac{K_0+2}{3}\right)^2 \frac{RT\beta}{N} n_0$ and f and g are constants for the molecule. The intensity of the light scattered in a direction making an angle ϕ with the incident beam is shown to be

$$\frac{I_0}{r^2}\left[\frac{\pi^2}{18}\frac{RT\beta}{N\lambda^4}(K_0-1)^2(K_0+2)^2(1+\cos^2\phi) + \frac{\pi^2}{2}\cdot\frac{(K_0-1)^2}{n_0\lambda^4}\frac{r_1}{6-7r_1} + 12\cdot\frac{\pi^2}{2}\frac{(K_0-1)^2}{n_0\lambda^4}\cdot\frac{r_1}{6-7r_1}\right]$$

The expression reduces to the appropriate forms when the medium consists of isotropic molecules and when the medium is a vapour obeying Boyle's law.

The co-efficient of extinction is shown to be

$$\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}\cdot(K_0-1)^2(K_0+2)^2 + \frac{8\pi^3}{3}\frac{(K_0-1)^2}{n_0\lambda^4}\frac{6r_1}{6-7r_1}\left(1+\frac{2}{3}\gamma\right)$$

For a vapour obeying Boyle's law, this becomes

$$\frac{8\pi^3}{3}\frac{(K_0-1)^2}{n_0\lambda^4}\frac{6+3r_1}{6-7r_1}$$

4. The observed values of the imperfection of polarisation in liquids are compared with the calculated values and the former are found to be much too small. This seems to indicate that the assumption of random orientation of molecules in liquids is not valid.

I wish to express my best thanks to Prof. C. V. Raman for his kind interest in the work and for his valuable suggestions.

XI. Electromagnetic Theory of the Scattering of Light in Fluids—Paper B.

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Introduction.

In a previous paper,[1] the author has worked out a theory of the scattering of light in fluids both for the case when the medium is composed of isotropic molecules and when it is composed of simple anisotropic molecules with random orientation. Since writing the above, there have appeared articles of great interest by Dr. Cabannes [2] [3] and Prof. L. V. King [4] dealing with the same subject. Some of the arguments and conclusions of these investigators appear to me to be open to question, and in order to clear up the matter, it seems desirable to set forth in somewhat greater detail certain parts of my aforesaid paper. Moreover, it has been pointed out to me by Prof. Raman that there is an error in my investigation of the case of anisotropic molecules which makes it necessary to revise some of the calculations given there. It is proposed in the first part of this paper to discuss the case of anisotropic molecules more fully with the necessary corrections put in and compare the theoretical results with experimental data, and in the second and third parts to review and discuss the theories put forward by Cabannes and King.

[1] Proc. Ind. Assoc. for the Cultivation of Science, Vol. VIII, pp. 1-22. We shall refer to this paper in the sequel as Paper A.

[2] Journal de Physique ; Ser. VI, Tome III, pp. 429-442 (1922).

[3] Comptes Rendus ; Tome 175, p. 875.

[4] Nature, May 19, 1923.

Proc. Ind. Assn. Cult. Sci. 8, 181–198, 1923.

I. Scattering by a Fluid composed of Anisotropic Molecules.

It was shown in Paper A that when a fluid medium of any density is composed of isotropic molecules, the intensity of scattering in any direction is given by the Einstein-Smoluchowski formula when in addition to the external field we take into account the polarisation field due to the neighbouring molecules. If the external field be parallel to Oz and of intensity Z, then the resultant field is also parallel to Oz and is of intensity $Z(K_0+2)/3$, K_0 itself being given by the well-known relation

$$\frac{K_0-1}{K_0+2}=\frac{4\pi}{3}n_0\,A.$$

Even when the molecules are anisotropic, the resultant field is still given by $Z(K_0+2)/3$ provided the molecules are oriented at random. In this case, however, K_0 is given by

$$\frac{K_0-1}{K_0+2}=\frac{4\pi}{3}n_0\left(\frac{A+B+C}{3}\right)^{1}$$

To get the intensity of light scattered in any direction from a unit of volume, we have to add together the contributions from all the molecules contained in it, due regard being paid to the phases of the waves scattered. In the case of isotropic molecules, the induced moments are all parallel to the external field and the direction of vibration in the scattered light is parallel to that in the incident. With anisotropic molecules, however, the directions of the induced moments are fixed in each molecule and the scattered light has in general also vibrations perpendicular to those in the incident light. In a medium composed of anisotropic molecules, the scattering can be supposed to arise out of two causes, one arising from the density fluctuations such as is contemplated in Einstein's theory and the other from the random character of the orientations of the anisotropic molecules.

[1] The notation of Paper A is used.

We may divide the volume of fluid illuminated by the incident light into a large number of equal elementary volumes δv, the linear dimensions of each of which are small compared with the wave-length of light in the medium, but yet so large compared with the size of a molecule that the fluctuations of density in one element may be independent of those in the neighbouring elements. Let us consider one of these elements with its centre at O. In order to get the intensity at any instant of the light scattered from δv, we have to square the algebraical sum of the components of the electric vector from the different molecules, and to get the average intensity over a finite interval of time, we have to calculate the average value of this quantity in a large number of independent trials in each of which the closeness of packing of the molecules and their orientations are redistributed according to the principles of statistical mechanics. If the incident light be plane-polarised with the electric vector Z parallel to OZ and the direction of propagation be Ox, then at a point P on the y-axis distant r from O, the x-component of the electric vector due to scattering from a molecule at O is given by

$$\frac{p^2}{c^2 r} \mathrm{M}_x$$

where

$$\mathrm{M}_x = \mathrm{Z}\left(\frac{\mathrm{K}+2}{3}\right)[\sin\theta\cos\theta\cos\psi(\mathrm{C}-\mathrm{A}\cos^2\phi-\mathrm{B}\sin^2\phi)$$

$$+(\mathrm{A}-\mathrm{B})\sin\theta\sin\psi\sin\phi\cos\phi],$$

and θ, ϕ, ψ are the Eulerian angles defining the orientation of the principal axes of the molecule.

From all the molecules contained in δv the value is

$$\frac{p^2}{c^2 r} \Sigma \mathrm{M}_x$$

Since δv contains a large number of molecules with their orientations at random, $\Sigma \mathrm{M}_x$ would in general be small,

since positive and negative values of M_x are equally probable. But it is also possible the values of M_x are all positive or all negative, or that the sum of all the positive values is just equal to the sum of all the negative values. These are extreme cases; at any trial, there would in general be a slight excess of the sum of all the positive values over the negative and *vice versa*. Thus, although in a large number of trials, ΣM_x would be zero, $(\Sigma M_x)^2$ would not be. As the late Lord Rayleigh [1] has shown, when the value of M_x is as often positive as negative,

$$\overline{(\Sigma M_a)^2} = n\overline{M_x^2}\,\delta v$$

where $n\,\delta v$ is the number of molecules contained in δv. The average expectation of X'^2 from δv is thus

$$\overline{X'^2} = \frac{p^4}{C^4 r^2}\,\overline{M^{x^2}}\,.\,n\delta v.$$

$$= \frac{p^4}{c^4 r^2}\,Z^2\left(\frac{k+2}{3}\right)^2 f\,n\delta v$$

where $f = \frac{1}{15}(A^2+B^2+C^2-AB-BC-CA)$

When we take the average effect over a finite volume V,

$$\overline{X'^2} = \frac{p^4}{c^4 r^2}\,Z^2\left(\frac{k_0+2}{3}\right)^2 f\,n_0\,V. \qquad \ldots \quad (1)$$

The z-component of the electric vector at P in the wave scattered from a molecule at O is [2]

$$\frac{p^2}{c^2 r}M_z = \frac{p^2}{C^2 r}.Z\left(\frac{k+2}{3}\right)L_3$$

where $L_3 = C\cos^2\theta + B\sin^2\theta\sin^2\phi + A\sin^2\theta\cos^2\phi$

[1] Theory of Sound, Vol. I, p. 36.

[2] In paper A, the square of this expression multiplied by $n^2\delta v^2$ was taken to represent the intensity of the light scattered from all the molecules contained in δv. This is erroneous, since a part of L_3, namely that arising from the anisotropy of the molecule varies from molecule to molecule.

and k is the value appropriate to the density in δv. The value of L_3 averaged over all orientations is $(A+B+C)/3$ and the above expression can be written

$$\frac{p^2}{c^2 r}\cdot Z\left(\frac{k+2}{3}\right)\left[\frac{A+B+C}{3}+\left(L_3-\frac{A+B+C}{3}\right)\right]$$

The square of the z-component of the electric vector from all the molecules contained in δv is therefore

$$\frac{p^4}{c^4 r^2}\cdot Z^2\left(\frac{k+2}{3}\right)^2\left[\left(\frac{A+B+C}{3}\right)^2 n^2\delta v^2\right.$$

$$\left.+\left\{\Sigma\left(L_3-\frac{A+B+C}{3}\right)\right\}^2+2\left\{\Sigma\left(L_3-\frac{A+B+C}{3}\right)\left(\frac{A+B+C}{3}\right)\right\}\right]$$

The third term is zero when averaged over all orientations. In the second term, $L_3-\frac{A+B+C}{3}$ varies from molecule to molecule and may either be positive or negative, the average value over a large number of molecules with all possible orientations being zero. In such a case

$$\left[\Sigma\left(L_3-\frac{A+B+C}{3}\right)\right]^2=n\,\delta v\left[\overline{L_3^2}+\left(\frac{A+B+C}{3}\right)^2\right.$$

$$\left.-2\overline{L_3}\left(\frac{A+B+C}{3}\right)\right]=n\,\delta v.\ \frac{4}{3}f$$

because

$$\overline{L_3^2}=\tfrac{1}{15}(3A^2+3B^2+3C^2+2AB+2BC+2CA)$$

and

$$\overline{L_3}=(A+B+C)/3.$$

The first term varies from one volume element to another owing to the fluctuations of density and the attendant fluctuations of dielectric constant, and as in the case of isotropic molecules (Sec. 3 of paper A), the expectation of the square of the z-component in the light scattered from δv arising out of this cause is

$$\frac{p^4}{c^4 r^2}\,Z^2\left(\frac{k_0+2}{3}\right)^4\left(\frac{A+B+C}{3}\right)^2\frac{RT\beta_{n_0}{}^2\delta v}{N}$$

The total value of $\overline{Z^{1^2}}$ from a volume V is therefore

$$\overline{Z^{1^2}} = \frac{p^4}{c^4 r^2} Z^2 \left(\frac{k_0+2}{3} \right)^2 n_0 V \left[\left(\frac{A+B+C}{3} \right)^2 \gamma + \frac{4}{3} f \right] \quad \ldots \quad (2)$$

where

$$\gamma = \frac{RT\beta}{N} n_0 \left(\frac{k_0+2}{3} \right)^2.$$

The ratio of the weak component to the strong in the light scattered along Oy is

$$\frac{\overline{X^{1^2}}}{\overline{Z^{1^2}}} = \frac{f}{\gamma \left(\frac{A+B+C}{3} \right)^2 + \frac{4}{3} f.}$$

When the incident light is unpolarised, the ratio is

$$r = \frac{2f}{\gamma \left(\frac{A+B+C}{3} \right)^2 + \frac{7}{3} f.} \quad \ldots \quad (3)$$

When the substance is in the form of a vapour so rare as to obey Boyle's law, this becomes

$$\frac{2f}{\left(\frac{A+B+C}{3} \right)^2 + \frac{7}{3} f}$$

Denoting this by r_1 and substituting the values of $\frac{A+B+C}{3}$ and f in terms of the constants of the medium,[1] the above becomes

$$r = \frac{6r_1}{\gamma(6-7r_1)+7r_1} \quad \text{or} \quad \frac{\gamma r}{6-7r} = \frac{r_1}{6-7r_1} \quad \ldots \quad (4)$$

The intensity of the transversely scattered light from a volume V at a distance r large compared with the linear dimensions of V is

$$\frac{p^4}{c^4 r^2} Z^2 \left(\frac{k_0+2}{3} \right)^2 n_0 V. \left\{ \left(\frac{A+B+C}{3} \right)^2 \gamma + \frac{13}{3} f \right\}$$

$$= \frac{Z^2}{r^2} \left\{ \frac{\pi^2 RT\beta}{9N\lambda^4} (k_0-1)^2 (k_0+2)^2 + \frac{\pi^2}{n_0 \lambda^4} (k_0-1)^2 \frac{13r_1}{6-7r_1} \right\} V.$$

[1] Page 17 of Paper A.

Substituting r_1 by r and introducing I_0 the intensity of the incident unpolarised light, this becomes

$$\frac{I_0 V}{r^2}\left\{\frac{\pi^2 RT\beta}{18N\lambda^4}(k_0-1)^2(k_0+2)^2\left(\frac{6+6r}{6-7r}\right)\right\} \quad \ldots \quad (5)$$

—— the same expression as was first proposed by Prof. Raman[1] from general considerations to represent the scattering of light in liquids.

In a direction making an angle χ with the incident light, the intensity is easily seen to be

$$\frac{I_0 V}{r^2}\left[\frac{\pi^2 RT\beta}{18N\lambda^4}(k_0-1)^2(k_0+2)^2.\left\{\frac{6-6r}{6-7r}(1+\cos^2\chi)+\frac{12r}{6-7r.}\right\}\right] \quad \ldots \quad (6)$$

and the coefficient of extinction becomes

$$\frac{8\pi^3}{27}\cdot\frac{RT\beta}{N\lambda^4}(k_0-1)^2(k_0+2)^2\left\{\frac{6+3r}{6-7r}\right\}.$$

Comparison with Experiment.

Prof. Raman and Mr. Seshagiri Rao[2] have compared the experimental values of the intensity of light transversely scattered by a number of liquids at the ordinary temperature with the values calculated according to (5), and shown that there is satisfactory agreement between the two except in the case of carbon disulphide which shows a very large depolarisation. In table I are included these values and also the values obtained by Messrs. Martin[3] and Lehrman. To reduce the two sets of values to the same standard, the intensities of scattering for ether have been assumed to be the same.

[1] "Molecular Diffraction of Light," p. 58, and C. V. Raman and K. Seshagiri Rao, Phil. Mag., March 1923.

[2] Phil. Mag., March 1923.

[3] Journ. Phys. Chemistry, Vol. 26, pp. 75-88 (1922).

Table I.—Intensity of transversely scattered light in liquids.

The intensities are expressed in terms of that of the polarised scattering of air at N. T. P.

Liquid.	Temp. °C.	$r = \frac{\text{Weak Component}}{\text{Strong Component}}$ (per cent.)			Intensity (calculated).	Intensity (observed)	Author.
		R & R	M & L	Adopted			
Water ...	30°	12·5		11·0	159	165	R & R [1]
			6·7			165	M & L [2]
Ether	30°	8·3		9·0	930	860	R & R
			10·0			860	M & L (assumed)
Methyl Alcohol ...	30°	15·1		11·0	512	495	R & R
			7·1			462	M & L
Ethyl Alcohol ...	30°	13·0		10·0	608	620	R & R
			7·8			485	M & L
n—Propyl alcohol	18°	...	8·5	8·5	546	630	M & L
Iso-butyl Alcohol	18°	...	3·5	8·5	610	679	M & L
Iso-amyl Alcohol	...	...	9·0	9·0	595	722	M & L
n—Hexane ...	...	...	10	10	835	969	M & L
Cyclo-hexane ...	...	...	8	8	816	750	M & L
Benzene ...	30°	39·8		48·0	3,600	3,135	R & R
			48·5			2,477	M & L
Toluene ...	30°	40·0		49·0	4,170	2,970	R & R
			49·0			2,804	M & L
Chloro-benzene ...	...	...	54	...	...	3,535	M & L
CS_2	30°	70		71·0	23,000	16,000	R & R
			71·0			10,850	M & L

[1] R. & R.; C. V. Raman and K. S. Rao.

[2] M. & L.: W. H. Martin and S. Lehrman.

The last four liquids which have a large depolarisation show a scattering power lower than that calculated.

In table II, the polarisation of the transversely scattered light in a number of liquids is calculated from the corresponding values in their vapours according to (4) and the results compared with experiment.

Table II.

Substance.	$\frac{\text{Weak Component}}{\text{Strong Component}}$ (per cent,)		
	Vapour.	Liquid at 30°C (calculated).	Liquid at 30°C (observed).
Ether	3·0	26·7	9·0
Benzene	6·5	50·4	48
CS_2	12·0	52	72
$CHCl_3$	3·0	26	15
CCl_4	3·1	37	11

Except in the the case of benzene, the calculated values show no agreement with the observed ones. With carbon disulphide, the observed value is higher than the calculated, while with the others, it is lower. This disagreement between observation and theory seems to show that the molecules in a liquid are not oriented at random. We should, however, still have expected the observed intensities to agree with the calculated, provided we make use of the *observed* values of the imperfection of polarisation. Although there is a good agreement for liquids showing a moderate depolarisation, it is no longer so for liquids showing strong depolarisation. It is remarkable that for these liquids, the observed intensities are *smaller* than the calculated ones.

2

Dependence of the polarisation of the scattered light on wave-length.

The question whether there is any change in the polarisation of the scattered light when the wave-length is altered is one of considerable interest. Experiments with ordinary gases in the visible region of the spectrum do not show any effect : but by reason of their greater depolarisation, liquids may show the effect, which would, however, depend not only on the anisotropy of the molecule, but also on the dispersive power of the substance. Equation (4) shows that even when r_1 remains constant, r would change with the wave-length, the value decreasing with decreasing wave-length, and if r_1 increases with decreasing wave-length (as we might expect it to do for theoretical reasons), the two would act in opposite ways. Previous work in the laboratory of the Indian Association with dust-free carbon disulphide and benzene had failed to show any change of the imperfection of polarisation with wave-length. Cabannes in his recent paper has obtained an effect with carbon disulphide, getting 66 per cent. with red light and 80 per cent. with blue. The experiments have been repeated by the author with the following liquids repeatedly distilled in vacuo, carbon disulphide, benzene, toluene, ethyl ether, ethyl alcohol and water ; none of them show a distinct change of r with wave-length. Strong sunlight was used for illuminating the liquids and colour filters for transmitting definite regions of the spectrum—cuprammonium for the blue and Wratten filters for the green and the red. With carbon disulphide, the imperfection was found to be 72 per cent. for white light and practically the same with the different colour filters. At any rate, the values lie between 70 and 75 per cent. The value for benzene was 48 per cent., for toluene 50 per cent. and for ether 9 per cent. In the case of alcohol and water, a difference between the

values has been previously recorded[1] when different colour filters are introduced in the path of the incident light, but a closer examination shows that this is not the effect sought for, but is due to the presence of a trace of fluorescence. This is made quite evident when the colour filters are transferred from the path of the incident beam to that of the scattered. The following tables give the values of the depolarisation.

Table III.—Ethyl Alcohol.

	$\frac{\text{Weak Component}}{\text{Strong Component}}$ (per cent.)		
	Red.	Green.	Blue.
Filter in incident beam ...	8·0	7·7	15·0
Filter in scattered beam ...	11·2	10·2	10·5

The value with no filter was 10·2 per cent.

Table IV.—Water.

(Repeatedly distilled in vacuo in pyrex glass bulb.)

	$\frac{\text{Weak Component}}{\text{Strong Component}}$ (per cent.)		
	Red.	Green.	Blue.
Filter in incident beam ...	10·0	10·0	17·5
Filter in scattered beam ...	10·2	10·8	11·0

[1] C. V. Raman, 'Molecular Diffraction of Light,' p 55 ; see also C. V. Raman and K. Seshagiri Rao, Phil. Mag., March, 1923.

The value with no filter was 10·8 per cent. The origin of the fluorescence has not yet been definitely ascertained. The alcohol used was the purest obtainable and it was distilled by cooling the condensing bulb with ice, keeping the other bulb slightly above the room temperature. As for the water, a specimen which had already been distilled over alkaline permanganate was used in the distillation bulbs (made of pyrex glass) and the distillations in vacuo were carried out very slowly. In spite of many re-distillations, the effect remained practically undiminished.

II. Cabannes's Theory.

The theory of scattering developed by Cabannes, though in some respects similar to the above, yet differs from it in certain fundamental points. In calculating the effect due to the neighbouring molecules, Cabannes follows the usual method (following Lorentz) of describing a sphere of radius R (small in comparison with the wave-length, but large compared with the linear dimensions of a molecule) about O, and considering the field at O to be made up with two parts, (1) the external field plus the field due to the molecules outside the sphere and (2) the field due to the polarisation of the molecules within the sphere. Lorentz and Rayleigh have shown that for a cubical arrangement of isotropic molecules, (2) is zero. Cabannes considers that although in a sufficiently long time, the components X_1, Y_1, Z_1 of this field may cancel, they would at any instant, owing to the irregularities in the distribution of molecules, differ from zero, and the quantities $\overline{X_1^2}$, $\overline{Y_1^2}$, $\overline{Z_1^2}$ would be finite. To calculate these mean values, he takes the mean square of the components $\overline{X_1^2}$, $\overline{Y_1^2}$, $\overline{Z_1^2}$ produced by a single molecule situated in all positions on the surface of a sphere of radius r and in all possible orientations and then sums up the effect for all the molecules contained between two spheres of radii d and R where d is the shortest possible distance between the centres of two neighbouring

molecules. On making the necessary calculations with the implicit assumption that each molecule scatters independently, he arrives at a formula for the imperfection of polarisation of the transversely scattered light from which it appears that even when the molecules of a medium are isotropic, there would be an imperfection of polarisation which would disappear when the density is very small, but which would increase with increasing density. He also obtains a relation between imperfection of polarisation in a liquid and its vapour in terms of the refractivity of the substance and the smallest possible distance between two molecules in the liquid state.

In adding the effects of the different molecules, Cabannes adds the squares of the electric intensities, thus assuming independence of phase between the radiations scattered by the different molecules—an assumption obviously invalid. The calculation of $\overline{X_1^2}$, $\overline{Y_1^2}$, $\overline{Z_1^2}$ also seems to be in error. It is true that in the case of a liquid, when we go down to the individual molecule, the actual field to which it is subject would vary from molecule to molecule, being in part dependent on the positions and orientations of the neighbouring molecules. The residual effect may be looked upon as due to the fluctuations from the cubical arrangement, and the exact magnitude of the fluctuations is not easy to calculate, but the scattering due to this cause may be expected to be small. For, consider a doublet at P with its axis parallel to OX. The electric intensity due to this will diminish as $\frac{1}{r^3}$ so that beyond a distance of a few molecular diameters from P, the intensity will be negligible. The space surrounding the doublet can be divided into two regions such that the x component of the flux of intensity in one is positive while that in the other is negative. These two regions *always accompany each other* and since the volume over which the intensity due to the doublet is sensible is small compared with a wave-length cube, we have to add together the electric intensities

of the scattered waves from the different molecules in this small volume. This sum will be of the second order of small quantities unless there is great asymmetry of distribution round P. The same remarks hold for the y and z components. Cabannes's method of calculation is tantamount to assuming that the positions of the molecules are perfectly random.

In his second paper, Cabannes has adapted Einstein's result to the general case of an isotropic fluid composed of anisotropic molecules by multiplying Einstein's expression for scattering by a factor derived from his own previous investigation. In view of the objections set forth above, this result also cannot be considered as acceptable.

Comparing Cabannes's theoretical results with experiment, it is not true that liquids have always a larger imperfection of polarisation than their vapours at low densities. As the temperature of liquid is raised, the imperfection of polarisation gets smaller and smaller and may reach a value much lower than that for the rare vapour. Experiments on benzene by the author [1] and by Martin and Lehrman [2] and on carbon dioxide by Raman and the author [3] furnish numerous instances of this. In the case of saturated vapour, an increase of density is accompanied by a diminution of the imperfection of polarisation.

Cabannes has deduced the smallest possible distance between the centres of two molecules in a liquid from the depolarizations in the liquid and vapour states. The values obtained are *much too small*. For, example, in benzene, the smallest distance is calculated to be 2·2 A. U, while the average distance [4] calculated from the density of the liquid on the hypothesis of a close packing of spherical molecules is 7·4 A. U.

[1] Physical Review, 21, p. 564 (1923).

[2] Journ. Phys. Chemistry, June 1923, pp. 558-564.

[3] In course of publication.

[4] Jeans, Dynamical Theory of Gases.

III. King's Theory.

Prof. King's extension of the theory of scattering to media composed of *complex anisotropic* molecules is of considerable interest. With regard to scattering by liquids, he considers that equally probable orientations of complex anisotropic molecules would result in the transversely scattered light being completely polarised. As we have seen in Part I, this is not true. The incompleteness of polarisation of the scattered light cannot, therefore, serve as a basis for the conclusion that liquids have a fine-grained crystalline structure.

In deriving his formula for the intensity of the scattered light in a direction θ with the incident beam, *viz.*,

$$\frac{r^2 I_\theta}{VI} = \frac{1}{2}\frac{\pi^2}{\lambda^4}(\mu^2-1)^2 . \quad \frac{6(1+\rho)}{6-7\rho} . \frac{RT\alpha}{N} \left\{ 1+\frac{1-\rho}{1+\rho}\cos^2\theta \right\},$$

King has apparently neglected to take into account the fluctuations of the polarisation field consequent upon the fluctuations of density. His formula therefore does not reduce to Einstein's in the case when the transversely scattered light is completely polarised. Again, it is not clear why King has used α, the adiabatic compressibility instead of the isothermal compressibility. The compressibility is introduced in finding the work done in changing the actual density at some volume element to the mean density under the condition of ideal thermodynamic equilibrium. Einstein's investigation [1] makes it quite clear that this work must be reckoned isothermally.

Conclusion.

Although the phenomena of molecular scattering do not furnish any definite evidence for the view that liquids possess a crystalline structure, the change of polarisation of a substance from vapour to liquid seems to show that we cannot

[1] Ann. der Physik, 33, 1275 (1910), see p. 1281.

assume that the molecules have random orientations. As was suggested by Prof. Raman in a letter to Nature,[1] there may be temporary groupings of molecules in a liquid having a higher degree of symmetry than the individual molecule. As already mentioned, with many liquids although the calculated values of the imperfection of polarisation are larger than the observed, the calculated intensities agree with the observed values: this can be explained by the assumption of such loose molecular groupings as Prof. Raman has suggested. The presence of these would not appreciably affect the refractivity and so long as their linear dimensions are small compared with a wave length, they would play the same part as the same number of single molecules oriented at random, with the difference that the anisotropic scattering would be altered.

Summary.

1. The theory of scattering by a fluid medium composed of anisotropic molecules in random orientation developed in a previous paper is revised and new expressions for the intensity and polarisation of the scattered light and for the coefficient of extinction derived.

With incident light unpolarised, the intensity of scattering in a direction making an angle χ with the incident beam is

$$\frac{I_0 V}{r^2}\left[\frac{\pi^2 RT\beta}{18N\lambda^4}(k_0-1)^2(k_0+2)^2\left\{\frac{6-6r}{6-7r}(1+\cos^2\chi)+\frac{12r}{6-7r}\right\}\right],$$

the polarisation of the transversely scattered light is

$$r=\frac{2f}{\gamma\left(\frac{A+B+C}{3}\right)^2+\frac{7}{3}f}$$

[1] Nature, March 31, 1923. See also Sir W. H. Bragg's note on the above.

and the coefficient of extinction

$$\frac{8\pi^3}{27}\frac{RT\beta}{N\lambda^4}(k_0-1)^2(k_0+2)^2\left\{\begin{array}{c}6+3r\\6-7r\end{array}\right\}$$

2. The theoretical results are compared with experiment. While there is good agreement between the observed and calculated values of the intensity of scattering for liquids having molecules of moderate anisotropy, there is a marked disagreement in the case of liquids with strongly anisotropic molecules.

The values of the imperfection of polarisation of liquids calculated from the corresponding vapour values show considerable deviation from the experimental values.

3. A reported change in the imperfection of polarisation of the transversely scattered light in carbon disulphide when the wave-length of the incident light is altered is not confirmed.

Some other liquids have also been examined and the effect has not been found in any of them. Incidentally, it is shown that a change previously observed in the imperfection of polarisation with water and alcohol is due to the presence of a trace of fluorescence.

4. An analysis is made of two recent papers by Cabannes on the theory of molecular scattering of light in fluids and it is shown that the assumption of independence of scattering by different molecules implicitly made therein and his calculation of the effect of local fields are not valid and that his theoretical conclusions are in disagreement with experiment.

5. Some critical remarks are offered about King's theory of scattering in liquids. It is pointed out that his assumption of a crystalline structure in liquids is unnecessary to account for the imperfection of polarisation of the transversely scattered light in liquids. Criticisms are also made regarding his formula for scattering.

The presence of loose molecular groupings having a higher degree of symmetry than the individual molecule would explain the observed low value of the imperfection of polarisation of the scattered light in many liquids.

The experimental observations contained in this paper were made at the Laboratory of the Indian Association for the Cultivation of Science. My warmest thanks are due to Prof. C. V. Raman for his kind interest in the work and for his valuable advice. The error in my previous investigation was pointed out by him.

The Diffraction of X-rays in Liquids, Liquid Mixtures, Solutions, Fluid Crystals and Amorphous Solids.

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1. Introduction.

When a narrow pencil of homogeneous X-rays passes through a thin layer of liquid and is received on a photographic plate, it is found that with a sufficient exposure, besides the central spot given by the undeviated pencil, there appears on the plate also a circular diffraction halo surrounding the

[1] A preliminary note in which the theory developed in this paper was indicated appeared in "Nature," Feb. 10, 1923, p. 185.

Proc. Ind. Assn. Cult. Sci. 8, 127–162, 1923.

centre and separated from it by a relatively clear space. This somewhat surprising observation was made by Debye and Scherrer [1] in the course of their work on X-ray diffraction. The same result has also been obtained in some recent X-ray studies by Hewlett [2] in which the ionization method was employed. Keesom and Smedt [3] have also studied the phenomenon in the case of several liquids by the photographic method and find that in some cases there is a weak second halo outside the first and even the suspicion of a third.

The behaviour in this respect of the special class of substances known as liquid crystals and studied by Lehmann and others is obviously of much interest. At the suggestion of Prof. Debye, observations were made by Hückel [4] with several of these substances, particularly with p-azoxyanisol and cholesteryl-propionate which were studied in (1) the solid crystalline, (2) the liquid crystalline, and (3) the liquid isotropic conditions. In the solid crystalline state, several sharp rings similar to those of other crystal powders were obtained, but remarkably enough, there was no notable difference shown by the photographs obtained with the isotropic and crystalline liquid states. In both cases a single diffraction halo appeared as in the case of ordinary liquids. It may also be mentioned that observations by Freidrich [5] on the scattering of X-rays by wax and other amorphous solids and by Jauncey [6] on the scattering by glass similarly show a maximum at a considerable angular distance from the undeviated pencil. It thus appears that in the three cases of an isotropic liquid, of a liquid crystal, and of an amorphous solid, we have essentially similar phenomena exhibited.

[1] Nachrichten Gottingen, 1916.

[2] C. W. Hewlett: Physical Review, XX, 1922, p. 688.

[3] Keesom and Smedt: Proc. Roy. Soc. Amsterdam, XXV, 1922, p. 118, and XXVI, 1923, p. 112.

[4] Hückel, Phys. Zeit, 1921, p. 561.

[5] Freidrich: Phys. Zeit. 14, 1913, p. 317.

[6] Jauncey: Phys. Review, XX, 1922, p. 405.

From the survey of the literature, it would appear that no satisfactory explanation of the appearance of the diffraction halo in these cases has so far been put forward. One view that has been suggested [1] is that the halo might be a diffraction-effect arising from the finite size of the molecule or the co-operation of the different atoms in it. This suggestion however must be negatived in view of Keesom and Smedt's observation that a liquid like argon which presumably has monatomic molecules shows the phenomenon in much the same degree as substances with more complex molecules. Another view that has been put forward by Hewlett [2] is that ordinary liquids possess something resembling crystal structure. The idea that in a liquid there are large groups of regularly arranged atoms is also put forward by A. H. Compton [3] in his recent report on X-ray scattering, when referring to observations by Hewlett and Duane. These hypotheses by Hewlett and Compton appear to us to be somewhat artificial; they have obviously been introduced in order to explain the observed effects, but lack independent justification. Keesom and Smedt have attempted to interpret their results as due to the interference of the effects of two neighbouring molecules, using for this purpose a formula proposed by Ehrenfest. Their theory, however, appears to us inadequate The essential features of the phenomenon are the region of the relatively very small intensity of scattering surrounding the central spot, and beyond this a moderately sharp diffraction-halo, having a much greater intensity than the scattering at large angles. Neither of these features is indicated by Ehrenfest's formula. To make the point clear we give below in Fig. 1C the curve of intensity for benzene reproduced from Hewlett's paper, and in Fig. 1A for comparison with it a graph of the intensity calculated from Ehrenfest's formula. It will be seen that

[1] Debye: referred to by Hückel.

[2] *Loc. cit.*

[3] Bulletin, National Research Council, U. S. A., No. 20, p. 14.

there is little in common between them. Finally we should mention an attempt which has been made by L. Brillouin [1] to explain the phenomena of X-ray diffraction in liquids and amorphous solids on the basis of the quantum theory of specific heats. We give in Fig. 1B a graph of the intensity in different directions drawn from his final formula. It will be seen that it bears no resemblance whatever to the observed result given in Fig. 1C.

We propose in this paper to approach the problem from an entirely different standpoint. In a series of publications [2] that have appeared in the course of the last two years, the authors and their co-workers have discussed the optical problem of the scattering of light in liquids under various conditions and shown that the experimental evidence amply confirms the

[1] Annales de Physique, Jan-Feb. 1922, pp. 88-122.

[2] 1. Notes by C. V. Raman in Nature, November 10, 1921, and several subsequent issues.

2. "Molecular Diffraction of Light" by C. V. Raman, Calcutta University Press, February, 1922.

3. "The Molecular Scattering of Light in Water and the Colour of the Sea" by C. V. Raman, Proc. Roy. Soc., April 1922, pp. 64-80.

4. "The Molecular Scattering of Light in Vapours and in Liquids and its Relation to the Opalescence observed in the Critical State" by K. R. Ramanathan, Proc. Roy. Soc., Vol. 102, 1922, pp. 151-161.

5. "The Molecular Scattering of Light in N-pentane" by R. Venkateswaran, Trans Chem. Soc., Vol. 121, 1922, p. 2655.

6. "The Molecular Scattering of Light in Liquid Mixtures" by C. V. Raman and K. R. Ramanathan, Phil. Mag., Jan. 1923, pp. 213-224.

7. "The Molecular Scattering and Extinction of Light in Liquids and the Determination of the Avogadro Constant" by C. V. Raman and K. S. Rao, Phil. Mag., March 1922, pp. 635-640.

8. "Electromagnetic Theory of Scattering of Light in Fluids" by K. R. Ramanathan, Proc. Ind. Assn. for the Cultivation of Science, Vol. VIII, Part I, pp. 1-22.

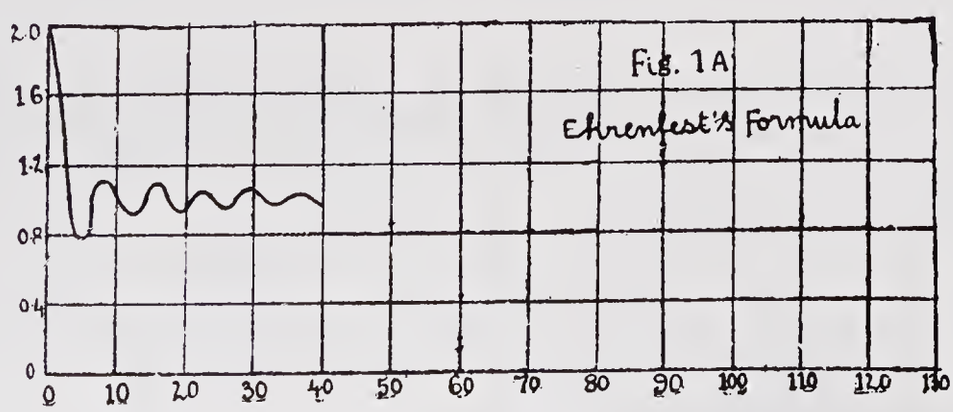
9. "The Visual and Photographic Albedo of the Earth," by K. R. Ramanathan, Astrophysical Journal, April, 1923.

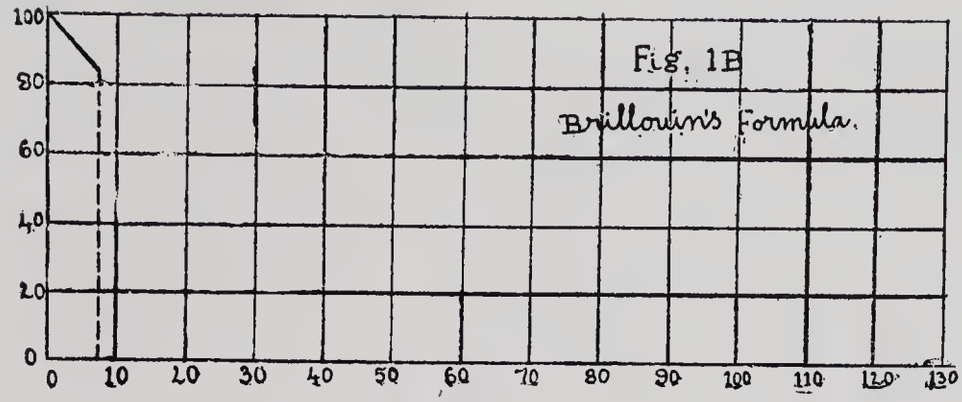
10. "The Molecular Scattering of Light in Benzene Liquid and Vapour" by K. R. Ramanathan, appearing in the Physical Review, 1923.

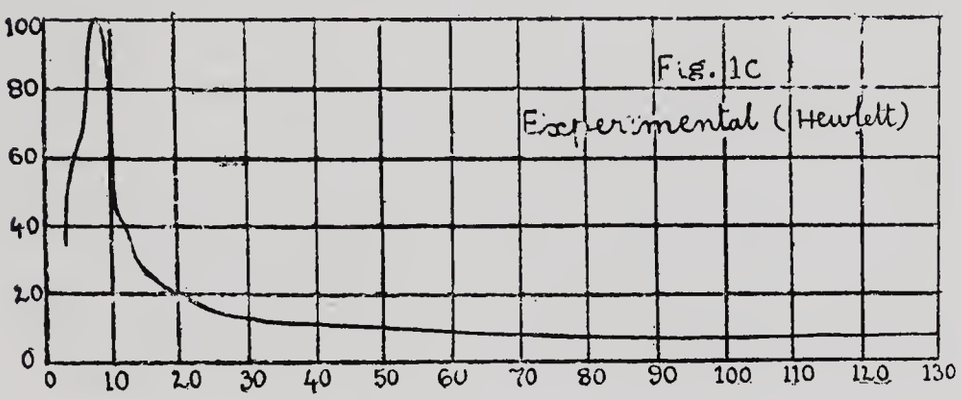
11. "The Molecular Scattering of Light in Liquid Mixtures" by J. C. Kameswar Rav, appearing in the Physical Review, 1923.

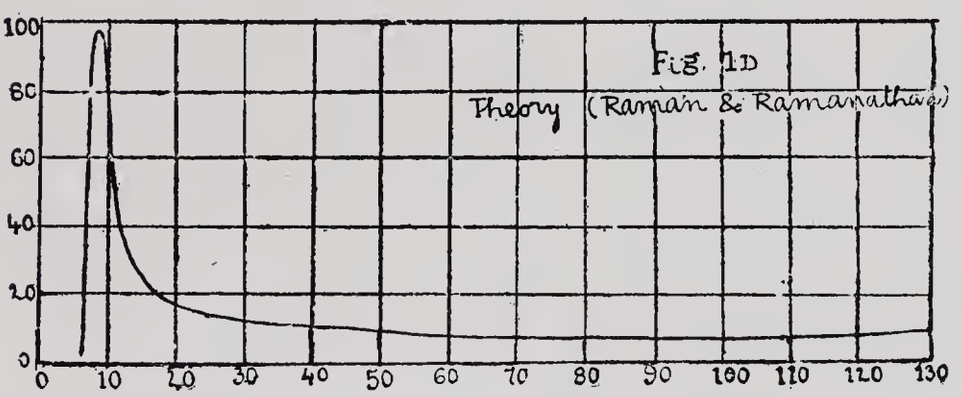
And other forthcoming papers.

statistical-thermodynamical theory of light-scattering developed by Smoluchowski and Einstein. The essential idea of the Einstein-Smoluchowski method is to treat a fluid as a continuous substance subject to local changes of density determined by thermodynamical considerations. Leaving out of account the effects due to the anisotropy of the molecules, the theory leads in the optical case to precisely the same results as those given by a more explicitly molecular treatment. This is due to the circumstance that the length of light waves is vastly greater than the scale of molecular dimensions, and hence the assumption involved in treating the substance as a structureless continuum does not lead to any appreciable error. The case is different however when we deal with the problem of diffraction of X-rays. The wave-length here is less than the average distance apart of the molecules, and in applying the statistical-thermodynamical considerations developed by Smoluchowski and Einstein, we have explicitly to take into account the fact that the medium is not continuous, but consists of a finite number of discrete particles. When this is done, the experimental results are explained quantitatively in a satisfactory manner. Fig. 1D gives the graph of intensity calculated from the formula we have developed in this paper. When account is taken of the imperfect homogeneity of the X-rays used by Hewlett, it will be seen that his experimental curve reproduces with remarkable fidelity the indications of theory.









2. Comparison with the optical scattering problem.

In order more clearly to appreciate the relations between the optical and X-ray problems, it is desirable here to give a brief outline of the theory of the former case. In Fig. 2, let ABCDE represent a unit volume of fluid (supposed of refractive index only slightly differing from unity) on which a parallel pencil of light is incident. Let n be the total number of molecules in it and let PPPP represent the in-falling rays and QQQQ the scattered rays in the particular direction under consideration. The volume ABCDE

may be divided into a very large number of slices by a series of equidistant planes perpendicular to the plane of the paper and equally inclined to the incident and scattered rays. It is assumed that each slice is thick enough to be several molecules deep and yet very thin compared with the wave length of the incident light. It is obvious that with these assumptions the scattered waves arising from the molecules in each slice may be taken to be all in identical phases. Let, A, B, C, D, etc. be successive

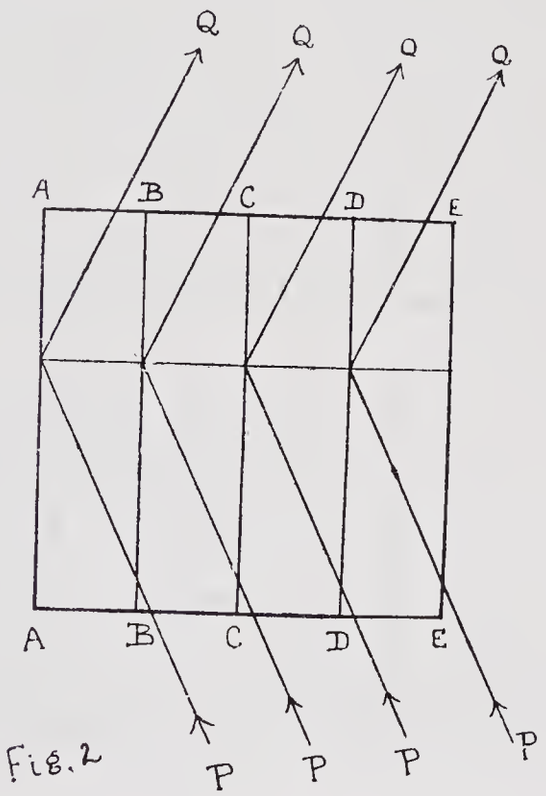


Fig. 2

planes which are situated at such intervals that the path differences of the scattered rays arising from layers adjacent to them differ by one wave-length. Each of the slabs AB, BC, etc., thus contains a considerable number, say r of the thin slices into which the medium was supposed to be divided. Then $AB=BC=CD=DE=\lambda/2 \sin \frac{1}{2}\theta$ where θ is the angle of scattering and λ is the wave-length of the incident radiation. Since the effects of all the molecules in a given slice, say the *pth*, of any one slab are taken to be in the same phase, they also agree in phase with those from the *pth* slice of every

other slab. The amplitudes of the scattered waves arising from all the molecules lying in the p^{th} slices of all the slabs may then be added up; and their resultant amplitude is proportional to the total number of molecules contained in the slices thus added together; denote this by n_p. The whole scattering may then be found by summing up the effects proportional to $n_1, n_2, \ldots n_p \ldots n_r$ of the successive slices, due regard being had to their respective phases, which are distributed at regular intervals from 0 to 2π. If $n_1 = n_2 = \ldots n_p = \ldots n_r$, the effects of the different slices would completely extinguish each other by interference. This corresponds to the case of a completely homogeneous medium, that is, a crystal at the absolute zero of temperature for waves of length great compared with its grating constant. In every other case, n_1, n_2 etc. would show fluctuations in value, and part of the incident energy would appear as scattered or internally reflected radiation. We know that $n_1 + n_2 + \ldots n_p + n_r = n$ and hence, denoting $n_1 - n/r = \Delta n_1$ $n_2 - n/r = \Delta n_2$ so on, the resulting effect would simply arise from the quantities Δn_1, Δn_2 etc. which represent the fluctuations from the mean density, the part due to the mean density itself disappearing by interference.

We can now consider the magnitude of the fluctuations Δn_1, Δn_2, etc. in different cases. We take first the case of an ideal gas which has been discussed by H. A. Lorentz.[1] Here the distribution of the molecules is a purely random one, and the average expectation of magnitude of the fluctuations Δn_1, Δn_2 etc. can be very simply shewn from probability considerations to be $\sqrt{n/r}$. If further, we make the assumption which is *a priori* justifiable in the case of an ideal gas—that the quantities Δn_1, Δn_2 etc. are as often positive as negative and vary quite independently of each other, then to find their aggregate effect, we add up *not* their amplitudes in their respective phases, but their intensities without regard to phase.

[1] Proc. Roy. Soc. Amsterdam, Vol. 13, 1910, p. 92.

The total scattering will thus be proportional to $r(\sqrt{n/r})^2$ or simply n, that is, to the total number of molecules in the fluid per unit of volume. This is the well-known Rayleigh law of scattering.

We next consider the case of a gas not obeying Boyle's law in which the distribution of molecules is no longer a random one. Here, applying Boltzmann's principle of entropy-probability, we find the mean value of Δn_1 to be, $n\sqrt{R\beta T/Nr}$ where R and N are respectively the gas constant and Avogadro constant for a gram-molecule, T is the absolute temperature and β is the isothermal compressibility of the fluid. Assuming as in the case of an ideal gas that Δn_1, Δn_2, may be as often positive as negative, and that their values are quite independent of each other, we get the total scattering by squaring and adding their intensities. The net result is thus proportional to

$$n^2 RT\beta/N \qquad (1)$$

and is thus proportional to the compressibility and to the absolute temperature and to the *square* of the density. For a gas obeying Boyle's law, β is the reciprocal of the pressure and it is easily seen that the expression reduces to n, which is the Rayleigh law of scattering.

For a liquid or very dense vapour of which the refractive index is sensibly greater than unity, the discussion proceeds on exactly the same lines as above, except that the local electromagnetic field due to the molecules themselves cannot be neglected in comparison with the field due to the incident wave and must be taken into account as in Lorentz's theory of dispersion. This increases the intensity of the scattered light without affecting its state of polarisation as shown in the paper (8) by Ramanathan quoted above. The scattering due to a unit volume is now proportional to

$$\left(\frac{\mu^2+2}{3}\right)^2 n^2 RT\beta/N \qquad \ldots \quad (2)$$

where μ is the refractive index of the fluid. When μ is sufficiently nearly equal to unity, (2) reduces to (1).

3. X-ray scattering at very small angles with the primary beam.

It will be seen that the simple treatment given above depends essentially on the possibility of dividing up the medium into slabs of thickness $\lambda/2\sin\frac{1}{2}\theta$ which can be further subdivided into several slices, each of which is many molecules thick, so that the fluctuations of density in any slice can be assumed to be independent of those in neighbouring ones. This, in general, is obviously possible only when λ is large, which is true in the optical case. When λ is comparable with molecular dimensions, and θ has any moderate value, each slab of thickness $\lambda/2\sin\frac{1}{2}\theta$ would be only a few molecules thick, and it would no longer be possible to assume that when it is sub-divided into thinner slices, the fluctuations in the different slices are uncorrelated, *i.e.*, independent of each other. In fact, it is easy to see that when the volume of the liquid is divided into very thin slices each only a molecule or so in thickness, any excess of density in one slice necessarily involves a deficiency in the adjoining slices and *vice-versâ*. The simple summation of the intensities of the scattered waves due to the density-fluctuations in the different slices, thus ceases to be admissible.

In one case, however, the Einstein-Smoluchowski theory may be applied as it stands to the problem of X-ray scattering. This is when the angle of scattering θ is very small. The thickness $\lambda/2\sin\frac{1}{2}\theta$ of the slabs AB, BC, CD, is then appreciable and may be made as large as we please by sufficiently decreasing θ. For instance if $\lambda = 0.71$ A. U., and $\theta = 10'$ of arc, $\lambda/2\sin\frac{1}{2}\theta = 239$ A. U. and each of the slabs AB, BC, etc., would, if we take the case of benzene liquid, be about 50 molecules thick. This thickness should be ample to enable the Einstein-

Smoluchowski theory to be applied. The isothermal compressibility β being 90×10^{-12} dynes per cm^2 for benzene, it is easily shown by calculation that the scattering given by formula (1) is 1/40 times smaller than in proportion to the number of molecules per unit volume. The scattering of X-rays at these small angles by liquids is thus almost negligible. Even for an angle of scattering of 2 degrees, a layer $\lambda/2\sin\frac{1}{2}\theta$ thick would be about 5 molecules deep, and though the Einstein-Smoluchowski theory would not be strictly valid, it could still be applied as a rough approximation, and the result indicated, *viz.*, that the scattering is very small would hold good.

It is thus seen to be a simple consequence of thermodynamics that in respect of scattering of X-rays through small angles, ordinary liquids stand in a position not very dissimilar to that of a complete crystal or of a crystal powder. The principal point of difference is that, in crystals, the compressibility is even smaller than in liquids and the scattering at small angles is therefore practically evanescent.

4. Explanation of the X-ray diffraction-halo of liquids.

As the angle of scattering θ is gradually increased, a stage is arrived at when the slab $\lambda/2\sin\frac{1}{2}\theta$ is only one or two molecules thick, and it is clear that the thermodynamical theory based on the idea that the fluid is a structureless continuum must then be modified. The essentially new feature that must be taken into account is that the fluctuations of density in neighbouring slices are no longer uncorrelated. Without going very deeply into the mathematical theory, it is easy to understand in a general way the nature of the results to be expected. For simplicity, we shall consider the case of a liquid which has only a very small compressibility, and in which consequently the thermal fluctuations of density are very small ; this means again that the molecules tend to be distributed in space in a manner approaching uniformity,

and not chaotically as in a gas. If, as before, there be n molecules per unit of volume, it is convenient to regard as the mean molecular distance a length λ_0 given by the formula

$$\lambda_0 = kn^{-1/3}$$

where k is a number of the order of magnitude of unity; regarding the exact value of k, we shall have more to say hereafter. Further, let the angle of scattering θ be such that $\lambda = 2\lambda_0 \sin \frac{1}{2}\theta$. Then each of the slabs AB, BC, etc., would on the average be just one molecule thick. It is obvious that in such a case, as has already been remarked, the supposition that when each slab is further subdivided into a number of slices, the effects of the molecules contained in the different slices would practically cut each other out by interference, would be entirely wide of the mark. In the first place, the number of the molecules in the different slices, would show fluctuations of *relatively* considerable magnitude. Further, instead of these fluctuations of density being entirely uncorrelated, they would be almost completely correlated in thr direction of amplifying the total observed effect. Foe assuming that out of the r slices into which the slab ABis, divided, the middle slice contains at any instant an exces number of molecules, the chance that at the same instant the slices near the face A or B contain a corresponding deficiency in molecules is very large. Since the scattered waves due to molecules in the middle and the outer faces of the slab differ in path by $\lambda/2$, the effects due to the excess in one slice and the deficiency in the others, would have *identical* phases, and their amplitudes would thus add up. Thus a very large scattering may be expected in the direction referred to, in fact many times greater than if the different molecules were regarded as scattering centres in random distribution of phase.

Theory thus leads us to expect a very large scattering in the direction θ where $\lambda = 2\lambda_0 \sin \frac{1}{2}\theta$, λ_0 being the mean molecular distance. Since as we have seen, the scattering is almost

nothing at small angles, it follows it should increase rather abruptly as θ increases and approaches the value $2 \sin^{-1}\lambda/2\lambda_0$. On the other hand, when θ reaches and passes this special value, we should expect a fall of intensity which is somewhat less rapid. For, as the angle of scattering is increased, the quantity $2\lambda_0 \sin \frac{1}{2}\theta$ becomes greater than λ, and hence the fluctuations of density in the different slices begin to neutralise each other's effects by interference, but not perfectly, owing to the want of correlation. At large angles, a considerable effect would be left over as the result of this incomplete correlation, and this may be expected to be still much greater than the Einstein scattering obtained in directions nearly parallel to the primary beam.

The theory thus clearly indicates that the diffraction-halo should be fairly sharp at its inner edge, and rather diffuse at its outer margin. These features are well shown in Hewlett's ionisation curves and Huckel's photographs already cited.

5. Analysis of molecular positions in a liquid and in mixtures and solutions.

In order to present the theory of the X-ray diffraction-halo exhibited by liquids as outlined above in a more complete mathematical form, we have to see how the theory of density-fluctuations which is based on the idea that a fluid may be regarded as a continuum should be modified so as to take into account its actual coarse-grained structure. From general thermodynamical considerations, it is clear that the distribution of the molecules in any small volume of liquid can neither be absolutely uniform and geometrically regular and periodic as in a perfect crystal, or absolutely chaotic as in an ideal gas. The character of the distribution as influenced by the thermal agitation and other factors must in fact be intermediate between these two extreme types. The density of matter present must fluctuate

from place to place and these fluctuations of density may be viewed in two rather different aspects. The first way of regarding them is that adopted by Einstein and Smoluchowski, that is, to ignore the independent existence of discrete molecules and confine attention to the total quantity of matter present in volumes which are small enough to be beyond the limit of microscopic observation, but large enough to contain a great number of molecules. This is quite sufficient for the purpose of dealing with the optical problem and also the X-ray scattering at very small angles. The second way of regarding the matter is to take cognisance of the individual molecules and of their movements in order to discuss and analyse the fine structure of the liquid, and this is necessary when we discuss the scattering of X-rays at larger angles. When we consider the fluctuations of density from the first point of view, their magnitude may be predicted completely from a knowledge of the compressibility of the matter in bulk, and it is unnecessary to know either the weight of the molecules or their size and shape. The fine structure of the liquid on the other hand can only be fully determined if we know the properties of the individual molecules. The thermal agitation is *one* of the factors that must be considered in carrying out this analysis of the positions of the molecules in any state of aggregation of matter, but that it is not the only factor is a fairly obvious proposition. To realise this, we have only to recall the extreme case of a crystal at the absolute zero of temperature. Here we have no "thermal" fluctuations of density, but the structure exhibits complex periodic fluctuations of density that do not vary with time.

As a preliminary to the more complete analysis of positions of molecules in a liquid, we shall first set out clearly the theory of density-fluctuations in a liquid in the simpler form sufficient for the optical problem.

Thermal fluctuations of density: Let us assume that the fluid is enclosed in a cube of edge-length L each way in the

fluid, the co-ordinates of any point within this volume lying between the limits

$$0<x<L$$

$$0<y<L$$

$$0<z<L.$$

Let the density of the liquid in any small region be denoted by

$$\rho, \text{ where } \rho=\rho_0+\Delta$$

ρ_0 being the average density, and Δ the fluctuation. The work done in compressing the fluid contained in any small volume V so that its density is increased by Δ is

$$\frac{1}{2}\cdot\frac{1}{\beta}\left(\frac{\Delta}{\rho_0}\right)^2 V$$

and putting this equal to

$$\tfrac{1}{2}\,R\,T/N,$$

we get at once for the mean square of the fluctuation

$$\Delta^2=\rho_0{}^2.\ R\ T\ \beta/NV.$$

The same result may also be derived by assuming that the medium is traversed by plane sound-waves of different wave-lengths, whose energy is distributed in accordance with the equipartition principle. Following Einstein,[1] we may write

$$\Delta=\sum_l\sum_m\sum_n B_{lmn}\ Cos\,2\pi\ l\ \frac{x}{2L}\ Cos\,2\pi\ m\ \frac{y}{2L}\cdot Cos\,2\pi\ n\ \frac{z}{2L}$$

where l, m, n, are positive integers. The potential energy in the sound-wave whose amplitude is B_{lmn} when integrated over the volume L^3 is easily shown to be

$$\frac{L^3}{16}\cdot\frac{B^2{}_{lmn}}{\rho_0{}^2}\cdot\frac{1}{\beta}$$

[1] Annalen der Physik, 1910, Band 33, p. 1283.

The law of distribution of each B_{lmn} is thus

$$C \exp. \left\{ \frac{-N}{RT}. \frac{L^3}{16}. \frac{B^2_{lmn}}{\rho_0^2}. \right\} d B_{lmn}$$

where C is a constant, and it follows that the mean value

$$\tfrac{1}{8} \overline{B^2}_{lmn} = \rho_0^2 . RT\beta/NL^3$$

which is identical with that given above, since

$$\overline{\Delta^2} = \tfrac{1}{8} \overline{B^2}_{lmn}.$$

This method of analysing the irregular distribution of molecules in a fluid into a system of sound-waves in a continuous medium is of course merely a convenient mathematical artifice. Einstein adopts it in his paper and shows that for each given direction, it is sound-waves of a particular wave-length that are chiefly responsible for the scattering of light; this wave-length λ_1 is connected with the angle of scattering θ and the wave-length of the light λ inside the fluid by the formula

$$\lambda = 2 \lambda_1 \sin \tfrac{1}{2}\theta$$

The wave-length of the sound waves which are chiefly effective is thus, except for very small angles of scattering, of the same order of magnitude as the wave-length of the incident radiation.

In order that the thermal energy of the fluid may be identified with the energy of propagation of sound waves in it, it must, as is well-known, be assumed that the sound-wave spectrum is limited on the short wave-length side, the smallest permissible wave-length λ_2 being given by the expression

$$\lambda_2 = n^{-\frac{1}{3}} . \sqrt[3]{\frac{4\pi}{9}} = 1 \cdot 118 \cdot n^{-\frac{1}{3}}$$

It is thus clear *primâ facie* that Einstein's method of considering the problem of scattering must fail when the wave-length of the incident radiation and the direction of observation considered are such that the sound-waves chiefly responsible

for the scattering have a wave-length equal to or less than this limiting wave-length which is determined by the structure of the medium. We have already shown however, that even before this limit is reached, the influence of the discrete structure begins to be felt and the conception of sound-waves in a continuous medium ceases to be appropriate as a method of dealing with the scattering problem.

Analysis of Fine Structure of Liquids : In the foregoing application of the Fourier analysis to the determination of the thermal fluctuations of density, it was tacitly assumed that apart from these fluctuations, the fluid itself could be regarded as a uniform continuum. This limitation must now be dispensed with, and the Fourier analysis applied to the determination of the actual distribution of matter in the fluid. The result of the analysis would depend on the manner in which the molecules, or rather the electrons in them responsible for the scattering of X-rays, are dispersed in space. If they formed a regular space-lattice—(this contingency cannot of course arise in any actual liquid)—the analysis would indicate a definite periodicity in the distribution of matter with wave-length equal to the grating constant of the lattice. Actually, of course, we cannot expect such sharply-defined periodicities or "structural line-spectra" in a liquid. We should rather expect to get as the result of the analysis, a "continuous structural spectrum" having its chief peak of intensity at a wave-length equal to or comparable with the mean distance between neighbouring molecules. We have to find a formula which will indicate the distribution of intensity in the "structural spectrum." This cannot of course be done completely without a knowledge of the special characteristics of the molecules under discussion. But, by considering only the essential features of the case, it would appear that the problem can, at least approximately, be solved with a knowledge of only the general thermodynamic properties of the fluid.

Let us imagine a cube in the fluid, which is normally of edge-length λ_0 distended or compressed into a cube of edge-length λ_1 ; the work done in the process is given by the expression

$$\frac{1}{2}\cdot\frac{1}{\beta}\cdot\lambda_0^3\left(1-\frac{\lambda_1^3}{\lambda_0^3}\right)^2$$

where β is the isothermal compressibility of the fluid. Actually as the result of thermal agitation, the cube might change shape as well as volume. If we take the cube to remain always a rectangular parallelopiped, the three edge-lengths may each be either greater or less than λ_0. It is only one chance in eight that all the edge-lengths would be *greater* (or less as the case may be) than λ_0. The average work corresponding to a change of one of the edge-lengths from λ_0 to λ_1 may thus be taken to be

$$\frac{1}{16}\cdot\frac{1}{\beta}\cdot\lambda_0^3\left(1-\frac{\lambda_1^3}{\lambda_0^3}\right)^2$$

and its thermodynamic probability may in accordance with Boltzmann's principle be written as

$$A\cdot\exp-\left\{\frac{1}{16}\cdot\frac{N}{RT\beta}\cdot\lambda_0^3\left(1-\frac{\lambda_1^3}{\lambda_0^3}\right)^2\right\}\cdot d\lambda_1,$$

where A is a constant. If λ_1 be taken to represent a wave-length in the Fourier analysis of the distribution of matter in the fluid, the expression just written is the formula for "the distribution of intensity in the structural spectrum." The expression gives a peak at the wave-length $\lambda_1=\lambda_0$ with intensity falling off more or less rapidly on either side of the peak. It will be understood that here we are dealing with real periodicities in the distribution of matter, and not merely with fictitious mathematical periodicities as in the discussion of the thermal fluctuations of density. Further, these structural waves pass through the fluid in all directions, and

we may more appropriately write as the expression for the intensity in the structural-spectrum,

$$\text{B.exp.} - \left\{ \frac{1}{16} \cdot \frac{N}{RT\beta} \cdot \lambda_0^3 \left(1 - \frac{\lambda_1^3}{\lambda_0^3} \right)^2 \right\} d\lambda_1 \, d\Omega$$

where B is another constant, and $d\Omega$ is the elementary solid angle.

The problem is now to determine the wave-length λ_0 of the peak in the "structural spectrum." *Primâ facie*, we shall not be appreciably in error if we take λ_0 to be identical with the mean distance between neighbouring molecules in the fluid. The evaluation of this mean distance is a very important problem in kinetic theory which does not appear as yet to have been adequately discussed. For an ideal gas, Hertz[1] has shown the mean distance between neighbouring molecules tobe $0.554\, n^{-\frac{1}{3}}$ where n is the number of molecules per unit of volume. For a regular cubical arrangement of molecules, λ_0 is evidently equal to $1 \cdot n^{-\frac{1}{3}}$, and for the closest[2] possible packing $\lambda_0 = 2^{\frac{1}{6}} \cdot n^{-\frac{1}{3}} = 1.123 n^{-\frac{1}{3}}$. In a liquid, the arrangement of the molecules is intermediate in type between the absolutely chaotic distribution characteristic of an ideal gas and the regular arrangement characteristic of a crystal. Gans[3] has attempted to take into account the finite volume of the molecules in the calculation of the mean molecular distance, and found that with increasing density of the fluid, λ_0 increases from $0.554\, n^{-\frac{1}{3}}$ to $n^{-\frac{1}{3}}$ and even more. His treatment is however open to certain criticisms, and the numerical values given by him cannot be accepted as correct. The problem is considered afresh in a separate paper by one of us, and the general result emerges that for a liquid, λ_0 is

[1] Math. Annalen 67. 387, 1909.

[2] Jean's Dynamical Theory of Gases, 3rd Edition, p. 330.

[3] Phys. Zeit, XXIII, 1922, p. 109.

$k.\, n^{-\frac{1}{3}}$ where k is a fraction ranging from about 0.8 to 1.0 according to the nature of the liquid and its condition as to temperature, pressure, etc. λ_0 may also be expressed in terms of the mean linear dimension or diameter σ of the molecule under consideration. The theoretical discussion indicates that in liquids under ordinary conditions λ_0 is of the same order of quantities as σ but may be some 10% to 20% greater.

Liquid Mixtures and Solutions: As we have just seen, the "structural spectrum" of a liquid consisting of only one substance is determined principally by the mean distance between neighbouring molecules and by its compressibility. Passing on to the case of mixtures and solutions, it is not difficult to see that the structural spectrum should, like many other physical characters, be at least roughly an additive property. For, to a first approximation, the volume of a mixture is the sum of the volumes of its components, and hence it is legitimate to assume that the mean distance between two molecules of the same kind in a mixture does not differ notably from what it is in the pure components. Thus if we have a succession of at least three molecules of one kind

A A A

or three molecules of the other kind

B B B

in a line, we have periodicities which are the same as those in the pure components. On the other hand, if we have at least four molecules forming a chain in which the two kinds of molecules alternate,

A B A B

or

B A B A

we would have wave-lengths corresponding to the sum of the two just considered. In the conditions subsisting in a fluid,

the formation of periodic arrays of four or more molecules of this special type is relatively an improbable event, and hence we are justified in assuming that the "structural spectrum" of a mixture or solution would contain principally only those wave-lengths which occur in the pure components. The same reasoning indicates that the distribution of "intensity" in the structural spectrum in the neighbourhood of these principal wave-lengths would be much the same as in the pure components. Hence we may as a first approximation take the structural spectrum of a mixture to be determined by simple addition of the structural spectra of the pure components taken in the proper proportions.

A more exact discussion of the case of mixtures and solutions would involve a consideration of the changes of density and of compressibility which occur when the two substances are mixed, and the influence on the structural spectrum of the local spontaneous fluctuations of density and composition; the precise magnitude of these fluctuations may be determined thermodynamically from the data for the compressibility and partial vapour-pressures of the mixture. *Primâ facie*, the local fluctuations of *composition* of the mixture would have very little influence on the structural spectrum. For, we are only concerned with the average effect corresponding to the mean composition of the whole liquid. If the two components make up the structural spectrum in proportion to their respective concentrations, the average effect would be the same as if the liquid was uniform throughout and exhibited no fluctuations of composition. The fluctuations of *density* on the other hand are all-important, as in the case of a pure liquid. The *compressibility* of the mixture therefore enters in a fundamental way in the problem and where this shows marked deviations from the additive rule,[1] the distribution of

[1] For data regarding the compressibility of mixtures and solutions, see Cohen and Schut's Piezo-Chemie, Leipzig, 1919, pp. 113-142.

intensity in the structural spectrum would differ from that given by a simple superposition of the spectra of the two components. Any notable change of volume on mixture may also be expected to result in a shift of the positions of the peaks in the spectra.

6. Calculation of the Intensity of X-ray Scattering.

Having analysed the distribution of matter in the fluid into a "Structural spectrum," in other words, into a number of superposed periodic distributions of different wave-lengths, we proceed to determine the X-ray scattering at different angles by this structure. We ignore the periodicities of larger wave-length which may be identified with sound-waves traversing the medium and which, as we have seen, are only of importance when we discuss the scattering in directions nearly identical with the primary beam. For larger angles of scattering, the periodicities of shorter wave-lengths which arise from the discrete structure of the medium are the only ones that need be considered. It is obvious that each of the periodic distributions of matter into which we have analysed the structure of the fluid would cause an internal reflection or enhanced scattering of the incident X-radiation in the direction given by the Bragg formula

$$2\lambda_1 \sin \tfrac{1}{2}\theta = \lambda$$

where λ is the wave-length of the incident X-radiation and λ_1 is the wave-length under consideration in the structural spectrum. Since the structural waves traverse the fluid in all directions, the enhanced scattering or internal reflection corresponding to the wave-length λ_1 would occur in all directions coinciding with the generators of the cone of semi-vertical angle θ. Since λ_0 is the wave-length giving the peak of intensity in the structural spectrum, the special value of θ given by the relation

$$2\lambda_0 \sin \tfrac{1}{2}\theta = \lambda$$

gives the cone of greatest intensity of the scattered X-rays, and the scattering would be considerably less both for larger and smaller value of θ. The formation of a fairly well-defined circular diffraction-halo in the X-ray scattering by liquids is thus clearly explained on the conception of the structural spectrum.

From the standpoint of the electromagnetic theory, the problem of determining the effect of the periodic distributions of the matter forming the structural spectrum on the propagation of radiation through the substance is very similar to that solved by Einstein in his paper on light-scattering in fluids except that the law of distribution of intensity in the "Structural spectrum" is different from that in the "Sound-wave spectrum." In fact, we can obtain an expression for the scattering due to the "Structural spectrum" merely by a slight modification of Einstein's treatment for the "Sound-wave spectrum." In the optical problem, we have light-scattering of the same intensity in all azimuths when the incident wave is assumed to have its electrical vector perpendicular to the plane of observation. This is due to the fact that the sound-waves of different wave-lengths which, as explained above, are each separately responsible for the scattering in different directions, are all, in accordance with the equipartition principle, of the *same intensity*. In the "Structural spectrum," on the other hand, the periodic distributions of matter of different wave-lengths follow the special exponential law of intensity

$$A \exp. \left\{ -\frac{1}{16} \frac{N}{RT\beta} \lambda_0^3 \left(1 - \frac{\lambda_1^3}{\lambda_0} \right)^2 \right\} d\lambda_1$$

Observing, as before, that each periodic distribution of wave-length λ_1, is responsible for scattering in a specific direction, the distribution of intensity in the diffraction-halo should obviously follow the law of the structural spectrum very

closely. We may therefore write the intensity of the scattered radiation in any direction θ to be simply

$$C_1 \exp.\left\{-\frac{1}{16}\frac{N}{RT\beta}\cdot\lambda_0^3\left(1-\frac{\lambda_1^3}{\lambda_0^3}\right)^2\right\}$$

where λ_1 is given by the Bragg formula

$$\lambda = 2\lambda_1 \sin\tfrac{1}{2}\theta$$

and C_1 is a numerical factor.

A useful verification of the formula is obtained by considering the case of a fluid of great compressibility, *e.g.*, a gas. In such a case, β is very large and the formula indicates, as is otherwise to be expected, that the scattering is of equal intensity in all directions perpendicular to the direction of the electric vector in the incident rays. If the incident X-rays are unpolarised, we should multiply the numerical factor C_1 by $(1+\cos\theta)$ exactly as in the ordinary theory of light-scattering.

The numerical factor C_1 may be evaluated in the following way. In experiments on X-ray scattering, the wavelength λ is generally much smaller than the mean distance between neighbouring molecules. The concentration of the scattered radiation in the form of a diffraction-halo is due to the arrangement of the molecules not being a random one, and hence there existing a correlation of the phases of the waves scattered by neighbouring molecules,—agreement of phase and increased intensity in certain directions, disagreement of phase and diminished intensity in others. The problem is analogous to that of the diffraction of light by a large number of fine holes arranged in a roughly uniform manner in an opaque screen. We know that in such a case, the integrated intensity of the diffracted light in all directions

together is simply equal to the energy transmitted by any one aperture multiplied by the number of apertures. Exactly the same way, C_1 may be found by integrating the energy of the scattered radiation in all directions and putting it equal to the scattering by one molecule multiplied by the number of molecules in the volume under consideration.

7. *Comparison with Observations.*

In order to test the indications of the foregoing theory by comparison with experiments on the scattering of monochromatic X-radiation by liquids, we require to know the compressibility β of the liquid and the mean distance λ_0 between neighbouring molecules in the liquid. The latter quantity may be roughly estimated from the known molecular mass M and the density d of the liquid; the best way of finding it is however from the X-ray scattering itself. As is evident, the formula

$$C_1 \exp. \left\{ -\frac{1}{16} \frac{N}{RT\beta} \lambda_0^3 \left(1 - \frac{\lambda_1^3}{\lambda_0^3} \right)^2 \right\}$$

when graphed gives a strongly pronounced maximum at the wave-length $\lambda_1 = \lambda_0$, and the general shape of the curve reproduces with striking accuracy, the experimental curves obtained by Hewlett by the ionisation method. (See Fig. *1C* and Fig. *1D* above, in comparing which allowance should be made for the imperfect monochromatism of the X-ray pencil used by Hewlett). From the known wave-length of the X-rays used and from the angle of scattering θ_0 for maximum intensity, λ_0 may be found by using the Bragg formula

$$\lambda = 2\lambda_0 \sin \tfrac{1}{2}\theta_0$$

That λ_0 thus determined is of the same order of quantities

as the value of the mean molecular distance otherwise found is seen from the following table:

TABLE.

SUBSTANCE.	λ	$\theta_\circ$	$\lambda_\circ$	$\sqrt[3]{\frac{M}{d}} = n^{-\frac{1}{3}}$	$\lambda_o \cdot n^{\frac{1}{3}}$
Results of Hewlett.					
Benzene	·712A	8·5°	4·80A	5·27A	0·911
Octane	,,	8·1°	5·04A	6·45A	0·781
Mesitylene	,,	6·5°	6·28A	6·13A	1·024
Results of Keesom and Smedt—First paper.					
Oxygen	1·54A	27°	3·30A	3·59A	0·919
Argon	,,	27°	3·30A	3·61A	0·914
Benzene	,,	18°	4·92A	5·27A	0·934
Water	,,	29°	3·08A	3·09A	0·997
Aethyl alcohol ...	,,	22°	4·04A	4·57A	0·884
Aethyl aether ...	,,	19°	4·67A	5·55A	0·841
Formic acid	,,	24°	3·70A	3·96A	0·934
Results of Keesom and Smedt—Second paper.					
Oxygen	·712A	12·5	3·27A	3·59A	0·911
Argon	,,	13·0	3·15A	3·61A	0·873
Water	,,	13·44	3·04A	3·09A	0·984
Nitrogen	,,	11·34	3·60A	3·85A	0·935
Carbon disulphide ...	,,	13·23	3·09A ?	4·63A ?	0·667

The mean distance λ_0 between neighbouring molecules found from the X-ray data is in every case of the same order of magnitude as $n^{-\frac{1}{3}}$ where n is the number of molecules per unit of volume. The last column gives the value of k where $\lambda_0 = k.n^{-\frac{1}{3}}$. It is seen that k is generally about 0·8 or 0·9 as is indicated by theory. It is noteworthy that of the 5 common liquids reported upon by Keesom and Smedt in their first paper, water which has the smallest compressibility has a value of k which is practically unity, while for ether which is highly compressible, k has the relatively low value 0·841.

The compressibilities of the three liquids for which Hewlett has given scattering curves are respectively as follows :—

Benzene	...	90×10^{-12} dyne/cm^2
Octane	...	120×10^{-12} ,,
Mesitylene	...	75×10^{-12} ,,

The differences between these are distinctly too small to produce any notable variation in the sharpness of the halo according to the formula. Strictly speaking, however, the halo for octane may be expected to be slightly less sharp than that for benzene or mesitylene. Hewlett's curves seem to indicate that this is actually the case, though owing to the width of the slit used and other complications, the data cannot be regarded as sufficiently precise on the point. Accurate data are as yet not available for any other liquid. It would be of interest to find experimentally whether liquids of high compressibility, *e.g.*, ether, exhibit a more diffuse halo than others, and whether any effect is produced by raising the temperature of the liquid towards the critical point ; with rise of temperature and consequently increase of both T and β, the halo may be expected to broaden, and since λ_0 would increase with rise of temperature, the halo should also approach more closely the direction of the primary rays. The scattering at small angles should also increase in accordance with the Einstein-Smoluchowski formula. These indications of theory remain to be tested by observation.

The preceding calculations are based on the analysis of the fine structure of the liquid into a continuous "structural spectrum" having the mean distance λ_0 between neighbouring molecules as its dominant wave-length. While this analysis no doubt correctly represents the facts in broad outline, it leaves out of account the special features arising from the structural peculiarities of the individual molecules and their influence on the distribution of matter in a closely packed assemblage. Other periods, particularly those with wave-lengths much smaller than λ_0, may conceivably become prominent when a dense aggregation of matter is analysed. In such a case, fainter diffuse haloes may arise outside the principal one. Then again, anomalies may arise in the case of highly asymmetrical molecules in which, instead of a single value of λ_0, we may have two or even three separate values of the mean distance depending on the special relative configuration of neighbouring molecules. The principal halo would then itself exhibit a complicated structure which might become better defined at lower temperatures when the thermal agitation and its diffusing influence are minimised.

A convenient way of visualizing the complications that may arise in individual cases is to consider the powder diffraction-haloes obtained by the Debye-Scherrer method with the same substance in the solid crystalline state. It is well-known that with the finest powders in which the individual particles are microscopic or ultra-microscopic crystals, the diffraction-rings obtained by this method are relatively diffuse.[1] If we imagine the process of subdivision of the individual crystals continued gradually, a stage would be reached when the outer rings would practically all have merged into a diffuse general blackening of the photographic film and even the first few intense rings would have broadened out

[1] See, Szigmondy's Kolloid-Chemie, Appendix on the X-ray analysis of colloids, by Scherrer.

and merged into a single halo. If we imagine all the crystals broken up into individual molecules, we should still get a halo, because, as we have already seen, thermodynamic considerations ensure a certain degree of uniformity in the spacing of the molecules. In view of this analogy, it may be expected that some of the less prominent details of the powder-halo may also survive and find their counterpart in the liquid-halo, though diffused and modified by the expansion or contraction which takes place on melting.

The considerations indicated above suggest that it would be of great interest to compare the diffraction-halo shown in the liquid state with that shown by the same substance in the state of crystalline powder below its melting temperature. Unfortunately, as yet, sufficient experimental material is not to hand for making such a comparison. In two cases, however, that of water and benzene respectively, the necessary data are available. X-ray powder-photographs of ice have been obtained by Dennison[1] and the results have been discussed theoretically by Sir W. H. Bragg,[2] who has pointed out a defect in the experimental technique of Dennison's work. The spacings observed in A.U. are chiefly, 3·92, 3·67, 3·44, 2·68, 2·26, 2·07, 1·96, 1·92, 1·53, 1·37, 1·30, 1·17. The first four roughly group about a mean 3·42 A.U. and the next four which are nearly coincident give a strong halo at 2·05 A.U. Allowing for the contraction and re-arrangement which takes place on melting, thsee spacings are in general agreement with the first and second diffraction haloes found for liquid water by Keesom and Smedt. The X-ray powder photograph of solid crystalline benzene taken by Broome[3] shows extremely strong haloes corresponding to spacings of 4·90 and 4·46 A.U., a second prominent group of haloes corresponding respectively to spacings of 3·71,

[1] Physical Review, Jan. 1921.

[2] Physical Society's Proceedings, 1922, p. 101.

[3] Phys. Zeits., March 1923, Plate VI.

3·44 and 3·11 A.U. and a third group corresponding to a spacing of about 2·00 A.U. The first prominent halo of liquid benzene corresponds to a spacing of 4·80 A.U., while Hewlett's curves also show distinct bumps corresponding to spacings of 3·40 A.U. and 2·04 A.U. The agreement appears significant.

Finally, it may be remarked that observations on the X-ray diffraction by liquids consisting of molecules with extended chains of CH_2 groups and the like, *e.g.*, the fatty acids, would be of interest. No data appear to be available regarding these.

Leaving now the case of pure liquids, we may refer in passing to the case of liquid mixtures and of solutions. Wyckoff[1] has studied mixtures of benzene and carbon tetra-chloride, water and glycerol, methylene iodide and carbon tetra-chloride, and also aqueous solutions of potassium chloride and of alum. The X-ray diffraction-effects shown by the liquid mixtures tried were found by him to be more or less merely superpositions of the effects shown by the components separately. Those due to the aqueous solutions were practically similar to that of pure water. The results for mixtures are in agreement with the approximate theory already indicated. In the case of aqueous solutions, the dissolved material was probably insufficient in quantity to appreciably influence the observed results. Wyckoff has not studied the case of partially miscible liquids It would be of interest to examine some cases of this kind, special attention being paid to the phenomena observed in the immediate vicinity of the critical solution temperature and for small angles of scattering.

8. *Liquid Crystals.*

Hückel's result, already cited in the introduction, that no notable difference is observable between the diffraction haloes

[1] American Journal of Science, Vol. V, 1923, p. 455.

shown by "turbid" and "clear" anisotropic liquids readily receives explanation in the light of the foregoing theory and of the ideas regarding the constitution of these bodies put forward by Oseen in two recent memoirs.[1] Oseen considers separately two types of interaction between the molecules, (*a*) forces tending to alter the relative positions of their centres of gravity, and (*b*) couples tending to alter their relative orientation. The equation of state of the fluid is derived by statistical-thermodynamical considerations on the basis of the assumed laws of interaction between the molecules. Both theory and observation indicate that in the turbid anisotropic liquids, there are regions whose dimensions include many wave-lengths of visible light over which the molecules are (at least approximately) similarly oriented. Similarity of orientation does not however necessarily involve any special regularity of spacing [2] beyond what may be expected on known thermo-dynamical principles from the compressibility of the liquid. It is probable also that the orientations are not exactly identical but that there is only a mean direction about which they oscillate. The absence of rigidity clearly shows that the definite space-lattices characteristic of solid crystals do not exist in the "turbid" fluids. Since the X-ray pattern is determined by the spacing of the molecules, and since what is observed in the experiments is the aggregate effect of groups oriented in all possible directions, it is clear that the diffraction-halo of a turbid

[1] Stockholm Academy, Handlingar, Band 61, No. 16 and Band 63, No. 1, 1921.

[2] In this connection, it is of interest to refer to the experiments of Barker (Jour. Chem. Soc., 1906, Vol. 89, p. 1120) and Beilby on the influence of a set of regularly arranged molecules on the crystal formation of an isomorphous substance. Barker found that if a thin film of $NaNO_3$ be allowed to dry on a *polished* surface of calcite, the crystals of $NaNO_3$ had their edges parallel to those of calcite. Beilby has shown that even when there are intervening films of foreign material, the orienting influence was exerted through the films provided they were sufficiently thin. Therefore the existence of an orienting influence does not necessarily connote a definiteness of spacing. (Beilby—Aggregation and Flow in Solids, p. 102.)

anisotropic liquid would differ little from that of the clear liquid.[1] The observations of Hückel are thus readily understood.

A detailed comparison of the X-ray photographs for the solid crystalline, anisotropic liquid, and isotropic fluid states for p-azoxyanisol and cholesterylpropionate reproduced with Hückel's paper is instructive. For both substances, the diameter of the liquid halo is approximately the same as that of the most intense group of rings in the crystal-powder photograph. Further, the haloes for the anisotropic and of isotropic liquids state, though very similar, are not absolutely identical and show slight differences in detail. This is not surprising in view of the fact that the compressibility, and other physical properties depending on the molecular arrangement are not identical for the two states. Further studies in regard to this would be well worth undertaking.

The recent studies of Friedel and Royer [2] and of Friedel [3] on anisotropic liquids with equidistant planes are of great interest in this connection. Friedel characterises as the 'smectic' state an arrangement in which the molecules besides having a common direction are in addition arranged in equidistant parallel layers, and which is thus intermediate between the amorphous and crystalline states of matter. To use the phraseology of our present investigation, the "smectic" state is a state of aggregation for which the "structural spectrum" for a particular direction is similar to that of a crystal, but for perpendicular directions is similar to that of a liquid. The X-ray diffraction by the "smectic" state of matter would thus simultaneously exhibit the characters of a crystal and of a liquid in different

[1] The X-ray method of observation is thus in a sense less powerful than the optical one in this particular field. Detailed studies of the scattering of ordinary light by "turbid" anisotropic fluids in different directions and at different temperatures would be of interest in relation to the varying size of the molecular groups.

[2] Comptes Rendus, Dec. 1921, June, 1922.

[3] Annales de Physique, November, 1922.

directions. The observations of De Broglie and Friedel [1] on the X-ray diffraction by oleate films, and of Piper [2] and Grindley on the X-ray diffraction by soap-curds may be explained on this basis.

9. *Amorphous Solids.*

It is well-known that many liquids and liquid mixtures when freed from dust may be cooled much below the ordinary melting temperature without crystallization occurring, and that they then pass into a highly viscous or glassy condition.[3] The view has therefore gained general acceptance that vitreous or amorphous solids are really super-cooled liquids, the softening temperature being higher than that of observation. We have already seen that even in liquids, the positions of the molecules are not distributed at random but with a certain degree of regularity depending on the compressibility of the substance. Since, by lowering of temperature, the compressibility of a liquid generally diminishes, it follows that when the substance reaches the highly viscous condition, the molecules are arranged with not less than the degree of regularity characteristic of the ordinary fluid condition. The statement frequently made that in an amorphous solid, the molecules are disposed at "random" is therefore certainly erroneous. It is true we do not have that complete regularity of spacing and orientation characteristic of a crystal. Since an amorphous solid is optically isotropic, it follows that the orientation of the molecules does not lie in any particular direction. But the spacing of the molecules has a considerable degree of regularity. The "structural spectrum" of an amorphous solid is therefore very similar to that of a liquid.

[1] Comptes Rendus, March 12, 1913.

[2] Phys. Soc. of London, Proceedings, August 1923, p. 269.

[3] See for instance, G. Tammann, "Aggregat Zustand" Leopord Voss, Leipzig, 1922.

A valuable confirmation of the views expressed above is furnished by observations on the scattering of light in amorphous solids such as optical glass and in supercooled liquids. Observations with liquids such as salol (phenyl salicylate) which may be converted into glassy solids by sufficiently cooling them show that the light-scattering power in the glassy condition remains of the same order of quantities as in the fluid state. The fact that the optical behaviour of an amorphous solid is very similar to that of a liquid is a justification for inferring that in regard to X-ray diffraction as well, they should behave similarly. The observations of Jauncey by the ionisation method refered to in the introduction, and of Wyckoff (*1C*) show in fact that ordinary glass gives a diffraction-halo very similar to that of a liquid. This does not, as has sometimes been suggested, indicate that glass possesses a rudimentary crystalline structure. The diffraction-halo observed is truly characteristic of the amorphous or non-crystalline condition. The sharpness of the halo is a measure of the regularity in the spacing of the molecules. An extensive series of observations of the X-ray diffraction-halo given by liquids which are supercooled and made to pass into the vitreous condition would be of interest in order further to elucidate the nature of the amorphous condition, and particularly to determine whether, when the temperature is taken below the softening point, any further re-arrangement of the molecules takes place or not.

Incidentally, it may be remarked that the conception of the "structural spectrum" may also be usefully extended to the case of solids and of solid solutions which are not truly amorphous but consist of microscopic or ultra-microscopic crystals packed together. The smaller the crystals, the more diffuse and weaker would be the lines of the "structural spectrum" and the more nearly would the X-ray scattering approximate to that characteristic of a truly amorphous body.

10. Summary and Conclusion.

The paper considers the explanation of the diffraction-haloes observed when a pencil of monochromatic X-radiation passes through a film of liquid and is received on a photographic plate. Explanations previously suggested are discussed and are shown to be inadequate.

(1) The explanation of the phenomenon is shown to depend on the consideration that the positions of the molecules in liquids are not at random but possess a certain degree of regularity which can be estimated thermodynamically from the compressibility of the fluid.

(2) The Smoluchowski-Einstein theory of light-scattering in fluids cannot be applied as it stands to the problem of the X-ray scattering owing to the fact that it practically treats the fluid as a continuum, an assumption which is justifiable in the optical case but not in the X-ray problem where the wave-length in much smaller; it is essential here to take into account the discrete structure of the medium.

(3) For very small angles of scattering, however, the Einstein-Smoluchowski theory is applicable even in the X-ray problem, and an explanation is readily forthcoming why liquids scatter very little at such angles.

(4) For larger angles of scattering, the discrete structure of the medium is taken into account by analysing the distribution of matter in the fluid into a continuous "structural spectrum" which has its peak of intensity at a wave-length equal to the mean distance λ_0 between neighbouring molecules. The law of the "structural spectrum" is exponential and is given by

$$A \exp. \left\{ -\frac{1}{16} \frac{N}{RT\beta} \cdot \lambda_0^3 \left(1 - \frac{\lambda_1^3}{\lambda_0} \right)^2 \right\} d\lambda_1$$

(5) The X-ray scattering in different directions is obtained very simply by combining the law of the structural

spectrum with the Bragg formula,

$$\lambda = 2\lambda_1 \sin \tfrac{1}{2}\theta$$

and this gives a diffraction-halo with its maximum intensity in the directions for which $\lambda_1 = \lambda_0$. The curve of intensity of the scattering in different directions agrees well with the experimental results of Hewlett, and the mean molecular distance λ_0 with the value deduced from kinetic theory.

(6) A discussion of the case of liquid mixtures indicates that the X-ray diffraction-halo should be practically a simple superposition of the haloes due to the separate components, as has been observed by Wyckoff.

(7) Diffraction by anisotropic liquids is discussed and the experimental results obtained by Hückel, and by De Broglie and Friedel are explained.

(8) Very similar arguments explain the X-ray diffraction-halo shown by amorphous solids.

(9) Some of the finer details of the halo observed in the experiments are also discussed and are shown to be intelligible in the light of the theory set out.

1

The Polarisation of Resonance Radiation and the Duration of Excited State.[1]

By

K. R. Ramanathan, M.A., D.Sc.

Introduction.

According to Bohr, the emission of radiation from an atom is preceded by the transference of an electron from its normal stationary orbit to an orbit of higher energy and the radiation takes place during the return of the electron to its normal orbit. From his correspondence principle, the polarisation and intensity of light of a definite frequency emitted during any transition process can be co-ordinated with the configuration of the orbits and the amplitudes of the appropriate components of vibration in different directions. In the case of resonance radiation, the exciting agency is the electric vector in the incident light-wave, and, if the incident light is plane-polarised, we may expect that when just excited, the component of vibration corresponding to the transition would be greatest in the direction of the electric vector in the incident light. The polarisation of the emitted radiation would depend on the orientation of the plane of motion of the electron at the time of its return to the original orbit. When secondary radiation can be neglected, the circumstances that might alter the orientation and form of the orbits are (1) Perturbations due to internal or external fields of force and (2) Collisions with other atoms or molecules. If by reason of one or more of these causes, the orientations of the electron orbits have been rendered random before the quantum-jump takes place, the radiation would be unpolarised.

[1] Read before the Indian Science Congress—January, 1924. Revised August, 1924.

Proc. Ind. Assn. Cult. Sci. 9, 93-102, 1925-26.

The recent experimental results of Professor R. W. Wood and Mr. A. Ellett[1] on the polarisation of the resonance radiation of the vapours of mercury and sodium in weak magnetic fields are of considerable interest in this connection. In the case of the resonance radiation 2537A° in mercury vapour at a pressure of the order of ·0002 mm., a field of 1·5 gauss applied in the direction of the magnetic vector of the incident light was sufficient to reduce the polarisation of the light emitted in that direction from 90 per cent. to about 10 per cent. Various interesting features of polarisation as the direction of the magnetic field was altered are recorded. A simple general explanation of the observed phenomena can be given by taking into account the Larmor precession of the approximately elliptic orbit of the electron round the direction of the magnetic field and the finite duration of the excited condition of the atom.

For convenience of reference, it is useful to summarise in a tabular form Wood's detailed observations which were made on sodium vapour at about 180°C. OX denotes the direction of the incident beam of plane polarised light and OY the direction of observation. When the direction of the electric vector of the incident light was parallel to OZ, the polarisation of the resonant light was 5 per cent. in zero field and it required a field of about 100 gauss parallel to OY to destroy the initial polarisation.

TABLE I.

Direction of Electric Vector in incident light.	Direction of magnetic field (100 gauss).	Polarisation.
OZ	OY	Nil
OZ	OX	Strong (about 30 p. c.) with el. vector II OZ.
OZ	OZ	Strong with el. vector II OZ.
OZ	45° with OZ in XZ plane	Nil
OY	zero field	Nil
OY	OX	Strong with el. vector II OZ.
OY	OZ	Strong with el. vector II OX.
OY	45° with OZ in XZ plane	Strong with el. vector ⊥ field.

[1] Proc. Roy. Soc. A, Vol. 103, p. 396 (1923).

Results of the same general character were obtained with mercury vapour also, with the difference that the polarisation was much more pronounced and the various features came out with a much weaker field of about 2 gauss.

Simple Theory of the Changes of Polarisation in a Magnetic Field.

The effect of a magnetic field is to superpose on the motion of the electron a uniform rotation round the direction of the field, the frequency of rotation being $\pm$ He/4πmc.[1] We shall take the simple case when the resonance radiation is completely polarised in the absence of the field, as is nearly the case in mercury vapour. When the incident light is plane-polarised with the electric vector parallel to OZ and the light is observed along OY, the application of a magnetic field either along OX or OZ would cause the light to be polarised along OZ, because the rotation round OX or OZ cannot contribute anything to the X-component. As the magnetic field is gradually turned from OX to OZ, the axis round which precession takes place would also turn round and it is easily seen by decomposing the vibrations parallel and perpendicular to the field that the percentage of polarisation would first diminish to zero and again increase. The minimum of polarisation can easily be shown to occur when the magnetic field makes an angle θ with OX where $\tan^2\theta = 1/2$. This angle, which is nearly 35° differs appreciably from the 45° which Wood obtained with sodium vapour. When the electric vector is applied parallel to OY and the magnetic field is applied parallel to OX or OZ, the rotation of the orbits round the field would lead to strong polarisation, the stronger components being along OZ and OX respectively, and this will also be accompanied by an *increase* of intensity. All these results are in general agreement with Wood's observations.

[1] J. Larmor, Phil. Mag., 44, 503 (1897).

We cannot, however, expect quantitative agreement with the theory outlined above except in the case where the atom shows normal Zeeman effect. With atoms like sodium which exhibit an anomalous Zeeman effect, the effect of the magnetic field would not be a simple rotation round the direction of the field.[1] The 2,537 line of mercury also does not show a normal effect, but its Zeeman separation is of the normal triplet type with a separation $\frac{3}{2}$ times the normal value.

Period of Precessional Rotation and Duration of Excited State.

One interesting feature observed with mercury vapour was the gradual decrease of polarisation from 90 per cent. to 10 per cent. as the magnetic field along OY was increased from 0 to 1·3 gauss. The phenomenon admits of a simple explanation on the above theory. When the precessional rotation is very slow, most of the radiation would have taken place before the corresponding vibrations in the excited atoms have been deflected through an appreciable angle from OZ and the radiation would retain most of its initial polarisation. As the intensity of the field increases, the component of vibration along the original direction would diminish and that in a perpendicular direction would increase, until with large speeds of rotation the light would be completely unpolarised. Putting in numerical values, the period of precessional rotation $4\pi mc/eH$ round the direction of the magnetic field is $7\times10^{-7}/H$ sec, and according to the measurements of Wien[2] on the gradual decrease of intensity of the 2,537 line of mercury when positive rays are allowed to stream into a

[1] G. Breit (Phil. Mag., May, 1924) has succeeded in explaining the leading features of the polarisation of resonance radiation in sodium vapour on the lines of the quantum-theory of anomalous Zeeman Effect.

"Molrefraction von Ionen und Molekülen in Lichte der Atomstructur" by K. Fajan and G. Joos—Zeitschrift Für Physik, April, 1924, p. 1.

[2] Wien; Ann der Physik, 73, p. 483, 1924.

high vacuum, the intensity diminishes with time in the ratio[1] e^{-2at} where $2a=1\cdot02\times10^7$ sec.$^{-1}$ Let us consider a large number of atoms excited to resonance with vibrations parallel to OZ and rotated round the direction of the magnetic field OY with angular velocity ω. The intensity of radiation from the atoms whose corresponding vibration directions make an angle θ with OZ would be, on the average, a^2e^{-2at} and the average amplitude would be ae^{-at} where t is the time required to turn through an angle θ under the precessional rotation, and a is the amplitude of the corresponding vibration when $t=0$. Resolving along OZ and OX, squaring, and integrating over all atoms at different stages of radiation from $t=0$ to $t=\infty$, we get

$$\frac{Z}{X}=\frac{\int_0^\infty e^{-2at}\cos^2\omega t\,dt}{\int_0^\infty e^{-2at}\sin^2\omega t\,dt}$$

where Z and X are the components of intensity with vibrations along OZ and OX respectively. The integrals are easily evaluated and give

$$\frac{Z}{X}=\frac{\omega^2+2a^2}{\omega^2}$$

Hence, the polarisation as observed along the Y axis is measured by

$$\frac{Z-X}{Z+X}=\frac{a^2}{\omega^2+a^2}$$

[1] It does not matter for our present purpose whether this exponential decrease in intensity is due to the rate of decrease in the number of quantum-jumps or whether it is due to an exponential decrease with time of each elementary process of radiation. For a discussion, see G. Mie; Ann. der Physik, 73, p. 195, 1924.

This shows a gradually decreasing polarisation as ω is increased.

Substituting Wien's value of 2α in our expression, we obtain a series of values for the polarisation for different intensities of the magnetic field. These have been plotted in Figure I. Wood's experimental values have also been plotted for comparison. The *course* of experimental values of the polarisation is well reproduced by the theoretical curve. It should be remembered that we have assumed perfect polarisation for zero field, while the experimental value was 90 per cent.

Mean Interval between Molecular Collisions and Duration of Excited State.

There is yet another direction from which we can get some information regarding the duration of emission. Wood has observed that the intensity and polarisation of resonance radiation in mercury vapour are affected by admixture with other gases.[1] The addition of helium or argon increases the intensity while the addition of air or hydrogen diminishes it, but in all cases, the effect of the addition is to diminish the polarisation. It is obvious that the effect of some of the collisions of an excited mercury atom with a molecule of hydrogen or of air is to prevent the radiation taking place. But not all collisions are deadly, as is shown by the increasing imperfection of polarisation on increase of pressure. We may take it that a collision would disturb the electron-orbit of the excited atom; when the disturbance is mild, the effect will only be to change the configuration of the orbit thus disturbing the polarisation and to give it a slow rotation which would slightly affect the frequency of the emitted radiation, and when the disturbance is intense, the radiation

[1] Phil. Mag., Vol. 44, p. 1107 (1922).

of the proper frequency will altogether be prevented.[1] From the chemical behaviour of the molecules and their behaviour towards free electrons, we may expect that collisions with helium and argon would on the whole be mild and that they would get more and more intense in the order nitrogen, hydrogen and oxygen.

For the same mean interval between two collisions of a mercury atom with a gas molecule the effect on the polarisation of the resonance radiation would be less and less marked (and the destructive effect on the intensity more and more marked) as we proceed in the same order, for in the latter gases, only a smaller fraction of the excited atoms can stand the shock of a collision and yet retain the power to radiate.

The following table shows the changes of intensity and polarisation as the mean interval between two collisions is altered. The experimental data have been taken from Wood's paper. The mean interval between two collisions of a mercury atom with a gas molecule has been calculated from the formula

$$\frac{1}{t} = 2v_2 s_{12}^2 \sqrt{\frac{\pi}{h}\left(\frac{1}{m_1} + \frac{1}{m_2}\right)}$$

(Jeans, Dynamical Theory of Gases, Second Edition, page 268) where v_2 is the number of molecules of the gas per c.c, s_{12} the sum of the radii of a mercury atom and of a gas molecule assuming them to be spherical, and m_1 and m_2 are the masses of a mercury atom and of a gas molecule respectively. The diameter of a mercury atom has been assumed to be $3 \cdot 2 \times 10^{-8}$cm. as calculated from the atomic volume (Sommerfeld : Atombau und spectral linien, p. 122, 3rd edition). The diameter of the excited atom is probably greater than that of

[1] Klein and Rosseland's impact of the "second kind," Zeit. fur Physik, 4, 46, 1921.

the normal one and the mean intervals given below too large on that account. The collisions of two mercury atoms with each other have been neglected as the vapour pressure of mercury was very small compared with the pressure of the added gases.

TABLE II

Gas.	Pressure.	Mean interval between two collisions of a mercury atom with a gas molecule.	Intensity on an arbitrary scale.	Polarisation.
Argon	3 mm.	6×10^{-8} sec	5	Faint
	5 mm.	$3{\cdot}6 \times 10^{-8}$ sec	10	Gone
Helium	2 mm.	5×10^{-8} sec	4	Faint
	6 mm.	$1{\cdot}7 \times 10^{-8}$ sec	10	Gone
Air ($0{\cdot}8\ N_2 + 0{\cdot}2\ O_2$)	0·65 mm.	$2{\cdot}4 \times 10^{-7}$ sec	2·5	Strong
	4 mm.	4×10^{-8} sec	1·	Nearly Gone
	1 cm.	$1{\cdot}6 \times 10^{-8}$ sec	0·5	Gone
Hydrogen	0·65 mm.	9×10^{-8} sec	1·	Strong
	4 mm	$1{\cdot}5 \times 10^{-8}$ sec	0·5	Faint
	1 cm.	$0{\cdot}6 \times 10^{-8}$ sec	0·2	A trace

When the added gas is helium or argon, the interpretation of polarisation is not simple inasmuch as Wood has found that when mixed with these gases, the mercury atom can be excited over a small range of frequencies lying on either side of the proper resonating frequency, and we cannot *assume* that this resonant radiation would be as polarised as that excited by the core of the line. The case of air also is not simple, because we have here two kinds of collisions, collisions with nitrogen molecules and collisions with oxygen molecules. Of these, the former may be expected to give rise to some unpolarised light while the latter will be more effective in

causing a radiationless transfer of the electron. In hydrogen, which causes the most marked change in intensity, we have, I think, the least complicated case.[1] When the mean interval between two collisions of a mercury atom with a hydrogen molecule is 9×10^{-8} sec, the polarisation is strong, but when the interval has come down to $0\cdot6\times10^{-8}$ sec, it has become a mere trace. From this, we can infer that a considerable part of the radiation has taken place between two collisions in the first case and that only a small part has taken place in the second. Assuming an exponential decrease of radiation with time, it is easy to calculate the average amount of radiation in the interval between two collisions. We have to remember that the time during which radiation can take place may be anything from o to t as the atom may be excited at any instant between two collisions. We thus get for the average fraction of energy radiated in the interval between two collisions [2]

$$R=1-\frac{1}{2at}\left(1-e^{-2at}\right)$$

Adopting Wien's value of $2a$ for 2,536 line of mercury, we get the following values of R for various values of t.

TABLE III.

$t\times10^8$ sec.	R.
20	·57
10	·37
5	·22
2	·10
1	·05

[1] It is of interest to note that Franck and Cario have found that collisions of excited mercury atoms with hydrogen molecules cause them to dissociate. Such a collision will certainly be radiationless. (Zeit. fur Physik, 11, 161, 1922.)

[2] Cario, Zeit. fur Physik 10, 185, 1922. Also Mie, loc. cit.

Of the unradiated part 1—R, most of it would disappear on collision (being convert into other forms of energy) with the exception of a small fraction which would appear as unpolarised radiation. As T decreases, this fraction would increase and the polarised part R decrease, both causes tending to reduce the polarisation. Comparison of Table III with the figures for hydrogen in Table II show that this is sufficient to account for the leading features of the phenomenon.

The importance of obtaining further quantitative data in this field is obvious.

Summary.

1. The changes of polarisation of the resonance radiation of the vapour of mercury in weak magnetic fields which have been studied by Wood and Ellett can be explained by taking into account the Larmor precession of the orbit of the electron round the direction of the magnetic field and the finite duration of the excited condition of the atom.

2. The duration of excited state required to explain the decrease of polarisation in mercury vapour resonance when a magnetic field is applied parallel to the direction of observation and perpendicular to the incident beam of light is consistent with Wien's determination of the same quantity.

The changes of intensity and polarisation of the resonance radiation when mercury vapour is mixed with other gases can also be explained by assuming that there is a finite time during which the atom remains in the excited state, and that the effect of a collision is either to destroy the radiation, or to disturb the polarisation so as to make its direction random.

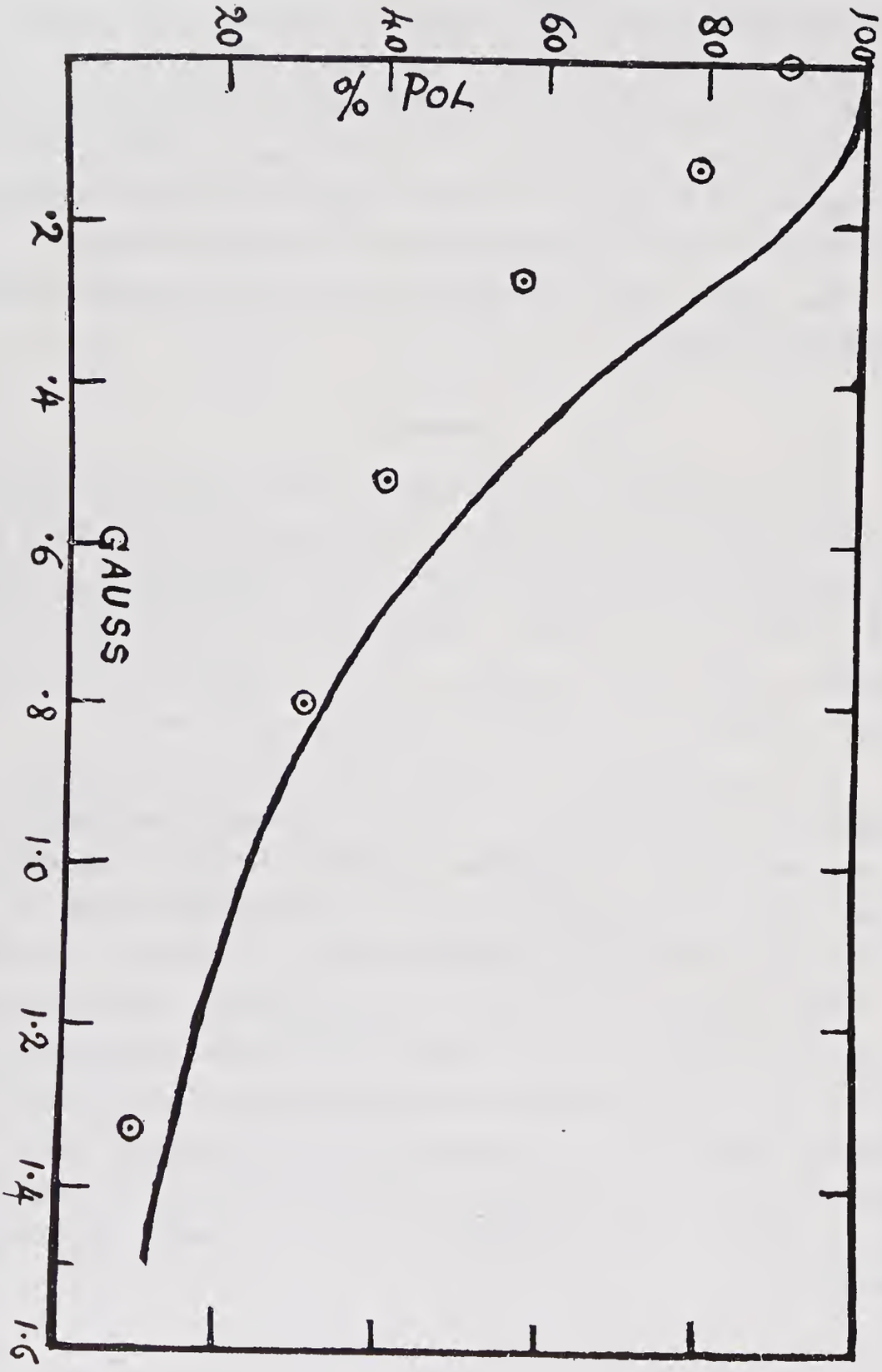


Fig. I.

THE TRANSPARENCY AND COLOR OF THE SEA

By K. R. Ramanathan

Abstract

The theory of the Secchi disk given by Shoulejkin[1] is discussed and a correct expression derived for the depth to which the disk, painted white, should be sunk in an ocean of pure dust-free water so as to be just visible. With ordinary paint the maximum depth is computed to be about 120 meters, whereas the greatest observed depth in the ocean is about 60 meters. The difference is due (1) to the presence of suspended matter and (2) to a possible extra absorption in the blue and violet. Contrary to the opinion expressed by Shoulejkin, it is shown that in the blue region the *brightness* due to molecular scattering alone would be appreciable, in fact about one-sixth that of blue sky. This is confirmed by rough observations made in the Bay of Bengal.

IN two recent papers,[1] Prof. Shoulejkin has discussed the question of the color of the sea and has published interesting experimental observations in connection with them. He is of the opinion that the return of light from the sea is mainly due to the scattering of light by small particles suspended in it, the color and intensity of the returned light being modified by the selective absorption of the water. While agreeing with Prof. Shoulejkin that in many cases the scattering of light by suspended particles is of primary importance, the writer wishes to point out that it is not always so. Shoulejkin has also derived an expression for the relation between the scattering and absorption coefficients of sea-water and the maximum depth to which a disk (painted white) should be sunk in order to be just visible. Making use of this relation, he concludes that in seas where water occurs in its purest form, and hence where molecular scattering[2] is mainly responsible for a return of light, there would be very little light returned from within the ocean and that the color and the brightness of such seas would depend mainly on the state of the sky at the time. Since this is contrary alike to theory and observation, it is felt desirable to examine Shoulejkin's paper in some detail.

Shoulejkin's arguments rest on his theory of the Secchi disk[1a] and on the expression for the brightness of the sea which he derived[1a]. It seems to the writer that serious errors have been made, especially in connection with the theory of the Secchi disk. Both on that account and on account of its intrinsic interest, it is proposed to discuss the problem afresh.

[1] Shoulejkin, (a) Phys. Rev. **22**, 85 (1923) and (b) **23**, 744 (1924).
[2] C. V. Raman, Proc. Roy. Soc. A **101**, 64 (1922) and
K. R. Ramanathan, Phil. Mag. **46**, 543 (1923)

Phys. Rev. 25, 386–390, 1925.

When a plate is gradually lowered in water to such a depth that it ceases to be visible, what we look for is the difference in *brightness* between the plate and the surrounding column of water. In a transparent medium, the brightness of an object which subtends a finite angle at the eye is independent of its distance, while in an absorbing medium, the brightness varies as $e^{-\gamma r}$ where γ is the coefficient of extinction in the medium and r is the distance.[3] When a matt surface of albedo 1 is sunk in water to a depth z, it will have a brightness $AI_0e^{-2\gamma z}/\pi$ where I_0 represents the intensity of the normally incident light at the surface of the sea. To get the apparent brightness of the disk, we have also to add to this the brightness of the superincumbent column of water due to scattering. If $2B/\lambda^4$ represents the scattering per unit solid angle by unit volume of water against the direction of the incident light, this amounts to

$$\frac{2BI_0}{\lambda^4}\int_0^x e^{-2\gamma x}dx=\frac{BI_0}{\gamma\lambda^4}(1-e^{-2\gamma x})$$

and the total apparent brightness of the disk is therefore

$$(A/\pi-B/\gamma\lambda^4)I_0\,e^{-2\gamma x}+BI_0/\gamma\lambda^4\,. \qquad (1)$$

The brightness of the surrounding unobstructed column of water is $I_0B/\gamma\lambda^4$ and the relative contrast is therefore

$$(A/\pi-B/\gamma\lambda^4)e^{-2\gamma x}/(B/\gamma\lambda^4)\,. \qquad (2)$$

In estimating what minimum relative difference in brightness we may reasonably expect to detect, we have to remember that at the depths at which the disks usually disappear in tropical waters, practically all the red, yellow and green have been cut off and the light is mostly indigo and violet where the sensitiveness of the eye in detecting differences of brightness is small and the fatigue is rapid; the disk is but a small patch in an otherwise continuous and uniformly bright area; and moreover, the observations are made from an unsteady support so that the eye cannot be properly focussed. Ten per cent will not, under these circumstances, be an overestimate for the minimum contrast necessary for proper seeing. Indeed, according to Buchanan,[4] the contrast should be very much larger. The value for the least perceptible difference in brightness adopted by Shoulejkin, 1/133, is decidedly too low. Even in calm days and with

[3] Shoulejkin's assumption that the coefficient of extinction as measured in transmission experiments is $\frac{1}{2}a/\lambda^4+f(\lambda)$ where a/λ^4 is the coefficient of scattering and $f(\lambda)$ the coefficient of absorption is erroneous. What is measured is $a/\lambda^4+f(\lambda)$.

[4] Buchanan, Nature, July 1910, p. 87.

large disks, it is doubtful if one could detect a difference of less than 5 per cent.

Another point of importance is the value of the albedo for the disk. With white light incident, the albedo for ordinary white paint is about 0.6, but the usual paints exercise an absorption in the blue and violet parts of the spectrum, so that in this region, the albedo is much less. When we go down to depths of 50 meters and more, the transmitted light is mostly of wave-lengths below .5μ and we cannot therefore use the usual value of the albedo. Buchanan's statement that at a depth of 25 fathoms, the brightness of the uninterrupted sea was of much *greater* intensity than that of the disk supports this.

Considering as an ideal case an ocean of dust-free distilled water and taking primary scattering alone into account, the following table gives the values of the brightness of a sufficiently large white disk sunk under different depths of water. The data for scattering and absorption coefficients are the same as those used in my paper on the color of the sea. The value of the albedo has been assumed to be 0.6 for all wave-lengths except the last two for which it has been taken to be 0.4 and 0.3 respectively.

TABLE I.

Proportion of incident light scattered per unit solid angle by a Secchi disk

Depth	.578μ	.546μ	.475μ	.436μ
50m	1.55×10^{-3}	9.1×10^{-3}	2.9×10^{-2}	4.3×10^{-2}
100	1.2	3.0	1.3	2.8
150	1.2	2.8	1.05	2.3
∞	1.2	2.8	1.0	2.1

To get the visual effect of all the wave-lengths taken together, we have to take the radiations in different spectral regions in proportion to the energies of the incident radiations and also to the corresponding luminous efficiencies. Remembering that the luminous efficiencies at .475μ and .436μ are only about 1/8 and 1/35 of that at .550μ (Ives), we can easily see from the table above that the maximum depth at which we can expect to distinguish a sufficiently large disk is about 120 meters.[5]

The greatest observed depth of disappearance of the disk, about 60 meters, is in the tropical parts of the Pacific ocean and in the Sargasso sea. In the transparent parts of the Indian ocean, the depth is about 50 meters. These are decidedly less than the depth calculated for pure

[5] We have in the above neglected the illumination of the disk and of the water by scattered light. A rough calculation shows that this will not greatly affect the depth of disappearance in pure water. A detailed calculation would however be of interest.

dust-free water; the difference may be due either (1) to scattering by suspended particles, such as were found by the writer to be present in small quantities in the Bay of Bengal, or (2) to an increase in the coefficient of absorption in the violet end of the spectrum or to both causes combined.

The presence of suspended particles affects the depth of sinking in two ways; it increases the coefficient of scattering which causes the return of a greater percentage of incident light from the water, the contribution of the surface layers being comparatively greater; it also reduces the transparency of the medium. A reference to Eq. (2) shows that both these would reduce the critical depth of sinking. When the quantity of suspended matter is, however, small, the increase in the scattering is mostly on the forward side of the incident light and the scattering against the incident direction is hardly affected. For example, with one of the samples from Bay of Bengal, the scattering was about 1.2 times that of dust-free distilled water between the angles 0° and 60° (measured from a direction opposite to the incident light), 1.5 times between 60° and 90°, 3.0 times between 90° and 120°, and 6 times between 120° and 180°. Since the solid angle contained between each of these limits is the same, namely π, the total scattering is increased to about 3 times that of pure dust-free water. But the total light returned from within the ocean is not increased in the same ratio, because the scattering against the direction of the incicent light is only slightly more than that of the dust-free water, and thus the return of light from within the sea is primarily due to molecular scattering. Although, therefore, the presence of these particles would to some extent diminish the depth at which an immersed white disk can be seen, it cannot account for the entire difference between the observed and calculated depths.

There is evidence to show that the actual absorption of sea-water in the violet end of the spectrum is really greater than that of dust-free distilled water. Even water from the deep-blue portions of the Bay of Bengal shows a very feeble but distinct green fluorescence when excited by blue and violet light. This implied an extra absorption in this region and this is, I think, another important reason why we are not able to see a white disk at depths greater than about 60 meters in even the most transparent parts of the ocean. Actual measurements of extinction coefficients in water collected from the transparent parts of the ocean would be of interest.

In connection with Shoulejkin's statement that molecular scattering by itself cannot give rise to any appreciable brightness of the sea, it may

be pointed out that according to the figures given in Table I, the brightness of a dust-free sea when viewed normally is in the blue region of the spectrum about one per cent of the incident intensity of illumination. When secondary scattering is taken into account, this will be raised to about 1.2 per cent. Now it is known that the average blue sky has about 1/7 the brightness of white paper illuminated by the zenith sun.[6] Taking the albedo of white paper to be 0.80, the brightness of the latter is AI_0/π i.e. about 25 per cent of the incident intensity of illumination, and that of the average blue sky is therefore 3.5 per cent. If we confine ourselves to the blue region of the spectrum, the value would be higher, say about 7 per cent. An ocean of dust-free distilled water would thus have a brightness about 1/6 that of the average blue sky, while sky-light normally reflected at the surface of the sea would give rise to a brightness of only 2 per cent of the sky-brightness. Some rough photometric measurements (with a blue filter) carried out by the author from the upper deck of a steamer in the blue waters of the Bay of Bengal between the hours 9 a.m. and 3 p.m. on a day when the sky was *very clear*, showed that the zenith sky was 4 to 5 times as bright as the sea when viewed nearly normally.

UNIVERSITY COLLEGE,
RANGOON, INDIA,
September 29, 1924.

[6] Recueil des Constantes Physiques, p. 209.

The Structure of Molecules in Relation to their Optical Anisotropy.—Part I.

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(Communicated by Prof. C. V. Raman, M.A., D.Sc., F.R.S.—Received June 23, 1924.)

One of the most significant facts relating to the scattering of light in gases is the imperfection of polarisation of the light scattered in a direction perpendicular to the incident beam. The late Lord Rayleigh* and Born† explained this phenomenon as being due to the optical anisotropy of the molecule, that is, to the fact that the polarisation induced in a molecule depends on its orientation with respect to the electric vector in the incident light. Lord Rayleigh's theory does not go into the question as to how the anistropy arises, but merely assumes that there are in each molecule three principal directions of vibration, along which the induced polarisations are different. If A, B, C are the moments induced in a molecule when its three principal directions are respectively along the direction of the electric vector in the incident light, then the ratio of the weak component to the strong in the transversely scattered light is given by

$$r = \frac{2(A^2 + B^2 + C^2) - 2(AB + BC + CA)}{4(A^2 + B^2 + C^2) + AB + BC + CA}. \qquad (1)$$

We now possess reliable measurements of the imperfection of polarisation in many gases and vapours, from the work of Lord Rayleigh‡ and of Raman and Rao.§ Recently there has been carried out at Calcutta further measurement of the same quantity, in a series of organic vapours, by Mr. A. S. Ganesan.|| Some of these results are collected together in Table I.

An examination of the table shows clearly the influence of the nature of the

* Rayleigh, 'Phil. Mag,' vol. 35, p. 373 (1918).

† Born, 'Verh. Deutsch. Phys. Gesell.,' vol. 20, p. 16 (1918).

‡ 'Roy. Soc. Proc.,' A, vol. 97, p. 435 (1920); vol. 98, p. 57 (1920); vol. 102, p. 190 (1923).

§ 'Phil. Mag.,' vol. 46, p. 427 (1923). Measurements have also been made by Gans ('Ann. der Physik,' vol. 65, p. 97 (1921)), and J. Cabannes (Jour. de Physique,' vol. 4, p. 429 (1923)).

|| Not yet published.

Proc. Roy. Soc. A. 107, 684–693, 1925.

Table I.

	$\frac{\text{Weak component}}{\text{Strong component}}$ in per cent.	Author.
Argon	0·46	R.
Mercury	Approximately complete	R.
Helium	<6·5	R.
Hydrogen	3·83	R.
	3·6	R. and R.
Oxygen	9·4	R.
	8·4	R. and R.
Nitrogen	4·06	R.
CO	3·4	Ramdas at Calcutta (not previously published).
CO_2	11·7	R.
	10·6	R. and R.
N_2O	15·4	R.
	14·3	R. and R.
CS_2	12·0	R. (earlier work).
	16·7	G.
Octane	2·7	G.
Benzene	6·6	G.
CCl_4	1·9	G.

R. = Lord Rayleigh. R. and R. = Raman and Rao. G. = Ganesan.

molecule on the value of the imperfection. Sir J. J. Thomson* has made suggestive attempts at connecting the variation of r with the departure of the shape of the molecule from spherical symmetry, but although among the mono-, di- and triatomic gases the value of the imperfection increases in general with the number of atoms in the molecule, this is by no means always the case. For example, octane, which is supposed to have a long molecule, shows even less imperfection than any of the diatomic gases in the table. It is, however, significant that in the case of the monatomic molecules, the imperfection is very nearly zero, and that among the polyatomic molecules, the smallest value of the imperfection is obtained for carbon tetrachloride, a molecule in which the chlorine atoms are presumably arranged at the corners of a regular tetrahedron.

The last-mentioned example suggests that a new way of approaching the problem is by considering the mutual influence of the different atoms composing a molecule. For example, in a diatomic molecule, when the electric vector is parallel to the line of centres of the atoms, the resultant polarisation would, owing to the mutual influence of the polarisations induced in each atom, be greater than if the atoms were far away from each other, while when the electric vector is perpendicular to the line of atomic centres, the polarisation

* 'Journal of the Franklin Institute,' vol. 195, p. 743 (1923).

would be smaller. On this view, a diatomic molecule must necessarily be anisotropic. With molecules containing more atoms, the anisotropy will depend on the nature and arrangement of the constituent atoms, and it may well be small even with long molecules. The recent success of Prof. W. L. Bragg* in explaining the double refraction of calcite and aragonite on somewhat similar lines makes it worth while to examine how far we can explain the observed effects by considering the mutual influence of the atoms.

Diatomic Molecules.

We shall assume that each atom by itself is isotropic, and that when placed in a periodic electric field behaves like a vibrating doublet placed at some point within the atom which we may call its "optical centre." Considering first the case of a diatomic gas like hydrogen in which both atoms are similar, let e be the charge on each equivalent doublet, m the mass of the vibrator and x the displacement. When the electric field E acts parallel to the axis of the molecule, the total electric intensity acting on one of the charges will be $\mathrm{E} + 2ex_1/d^3$ where d is the distance between the optical centres of the atoms. Hence

$$m\ddot{x}_1 + fx_1 = e\,(\mathrm{E} + 2ex_1/d^3),$$

where f is the restoring force on each charge per unit displacement.

When the periodicity of the electric intensity is introduced through the factor $\cos pt$

$$ex_1 = \frac{e^2/m}{n^2 - p^2 - 2e^2/md^3}\,\mathrm{E}, \qquad (2)$$

where $n^2 = f/m$.

The electric moment for the two atoms together is

$$\mathrm{AE} = 2ex_1.$$

Similarly, when the electric field acts perpendicular to the axis of the molecule,

$$\mathrm{BE} = 2ex_2 = \frac{2e^2/m}{n^2 - p^2 + e^2/md^3}\,\mathrm{E}.$$

When the molecules are oriented at random, the average value of $2ex$ will be given by

$$2\overline{ex} = \left(\frac{\mathrm{A}}{3} + \frac{2\mathrm{B}}{3}\right)\mathrm{E}$$

* W. L. Bragg, 'Roy. Soc. Proc.,' A, vol. 105, p. 370 (1924). Reference may also be made to a series of interesting papers by Dr. Silberstein in 'Phil. Mag.,' January, 1917, on "Molecular Refractivity and Atomic Refraction," etc.

and the refractivity

$$\mu^2 - 1 = 4\pi\nu\left(\frac{A}{3} + \frac{2B}{3}\right)$$

$$= \frac{4\pi\nu e^2}{3m}\left\{\frac{2}{n^2 - p^2 - 2e^2/md^3} + \frac{4}{n^2 - p^2 + e^2/md^3}\right\},$$

where ν is the number of molecules per unit volume. Writing

$$\frac{4\pi\nu e^2}{m(n^2 - p^2)} = R_0$$

and

$$\frac{1}{2\pi\nu d^3} = k,$$

it is easy to put this into the convenient form

$$\mu^2 - 1 = \frac{2R_0}{3}\left\{\frac{1}{1 - R_0 k} + \frac{2}{1 + \frac{1}{2}R_0 k}\right\}. \qquad (3)$$

The optical anisotropy which may be defined as A/B is given by

$$\frac{A}{B} = \frac{1 + \frac{1}{2}R_0 k}{1 - R_0 k}. \qquad (4)$$

We shall now consider a few simple cases.

1. *Hydrogen.*—From our assumption of the isotropy of each atom the molecule should have spheroidal symmetry. We can therefore write in equation (1) B = C, and we get

$$r = \frac{2(A^2 + B^2 - 2AB)}{4A^2 + 9B^2 + 2AB}.$$

Taking r for hydrogen to be 3·7 per cent. and solving, we get

$$A/B = 1{\cdot}66 \text{ or } 0{\cdot}543.$$

Consistently with our physical assumptions we adopt the first value, and from (4) we calculate $R_0 k = 0{\cdot}3047$. Using this value in (3) and taking R to be 0·0002812 (Cuthbertson's value for 0·486 μ), we get

$$R = 1{\cdot}328 \times 10^{-4}$$
$$\text{and } k = 2{\cdot}293 \times 10^{3},$$

leading to a value $d = 1{\cdot}37 \times 10^{-8}$ cm.* This may be compared with the value of the molecular radius calculated from mean free path phenomena $1{\cdot}34 \times 10^{-8}$ cm.†

* ν has been assumed to be $2{\cdot}708 \times 10^{19}$ per c.c.

† Jeans, 'Dynamical Theory of Gases,' second edit., p. 341.

2. *Nitrogen.*—$r = 4{\cdot}06$ per cent. $A/B = 1{\cdot}696$. $R_0k = 0{\cdot}3169$ from (4). Taking R to be $0{\cdot}0006024$ for $0{\cdot}486\ \mu$ and using (3), $R_0 = 2{\cdot}832 \times 10^{-4}$,

$$k = 1{\cdot}119 \times 10^3 \quad \text{and} \quad d = 1{\cdot}90 \times 10^{-8}\ \text{cm.}$$

while the kinetic theory free path value of the "radius" of a nitrogen molecule is $1{\cdot}90 \times 10^{-8}$ cm.

3. *Oxygen.*—For this gas we shall take $r = 8{\cdot}9$ per cent., the average of the values obtained by Rayleigh and by Raman and Rao.

The corresponding value of $A/B = 2{\cdot}211$ and $R_0k = 0{\cdot}4466$.

$$\text{Taking } R = 0{\cdot}000547 \text{ for } 0{\cdot}486\mu \text{ and } R_0 = 2{\cdot}384 \times 10^{-4},$$
$$k = 1{\cdot}874 \times 10^3 \quad \text{and} \quad d = 1{\cdot}46 \times 10^{-8}\ \text{cm.},$$

while the mean free path value of the molecular radius is $1{\cdot}81 \times 10^{-8}$ cm. As will be noticed, while the kinetic theory diameter of an oxygen molecule is somewhat less than that of a nitrogen molecule, the distance between the optical centres seems to be much smaller in the former case.

Triatomic Molecules.

Turning now to the case of a triatomic molecule like N_2O, CO_2, or CS_2, we can calculate its refractivity and optical anisotropy provided we know the structure of the molecule, the refractivities of the constituent atoms and the distance apart of the optical centres. For example, in the case of N_2O, let us suppose that the atomic centres are in a straight line, the oxygen being at the centre and let e_1 denote the charge on the equivalent doublet in the nitrogen atom, m_1 the mass of the vibrator and f_1 the restoring force per unit displacement. Let similar symbols with suffixes 2 denote the corresponding quantities in the oxygen atom. Then, when the electric field is parallel to the length of the molecule, the equations of motion of the charges in the nitrogen and oxygen atoms are respectively

$$m_1\ddot{x}_1 + f_1x_1 = e_1\left\{E + \frac{2e_2x_2}{d^3} + \frac{2e_1x_1}{8d^3}\right\}$$
$$m_2\ddot{x}_2 + f_2x_2 = e_2\left\{E + \frac{4e_1x_1}{d^3}\right\}, \qquad (5)$$

where d is the distance between the optical centres of the oxygen and nitrogen atoms.

Introducing the periodicity of the electric intensity through the factor $\cos pt$ and solving for e_1x_1 and e_2x_2, we get

$$e_1x_1 = \frac{R_1}{4\pi\nu}\,\frac{1 + R_2k}{1 - R_1k/8 - 2R_1R_2k^2}\,F, \qquad (6)$$

where

$$R_1 = \frac{4\pi\nu e_1^2}{m_1(n_1^2 - p^2)} \quad R_2 = \frac{4\pi\nu e_2^2}{m_2(n_2^2 - p^2)} \quad \text{and} \quad k = \frac{1}{2\pi\nu d^3},$$

and

$$e_2 x_2 = \frac{R_0}{4\pi\nu} \frac{1 + 15/8\, R_1 k}{1 - R_1 k/8 - 2R_1 R_2 k^2} E.$$

The total moment along the length of the molecule is

$$2e_1 x_1 + e_2 x_2 = \frac{2R_1 + R_2 + 31/8\, R_1 R_2 k}{1 - R_1 k/8 - 2R_1 R_2 k^2} \frac{E}{4p\nu} = AE, \text{ say.}$$

Similarly, when the electric intensity is perpendicular to the line of atomic centres, the equations of motion are

$$m_1 \ddot{x}_1 + f_1 x_1 = e_1\left(E - \frac{e_2 x_2}{d^3} - \frac{e_1 x_1}{8d^3}\right),$$

$$m_2 \ddot{x}_2 + f_2 x_2 = e_2\left(E - \frac{2e_1 x_1}{d^3}\right).$$

Solving,

$$e_1 x_1 = \frac{R_1}{4\pi\nu} \cdot \frac{1 - R_2 k/2}{1 + R_1 k/16 - \frac{1}{2} R_1 R_2 k^2}$$

and

$$e_2 x_2 = \frac{R_2}{4\pi\nu} \cdot \frac{1 - 15/16\, R_1 k}{1 + R_1 k/16 - \frac{1}{2} R_1 R_2 k^2}$$

and the corresponding moment is

$$2e_1 x_1 + e_2 x_2 = \frac{1}{4\pi\nu} \frac{2R_1 + R_2 - 31/16\, R_1 R_2 k}{1 + R_1 k/16 - \frac{1}{2} R_1 R_2 k^2} E$$
$$= BE.$$

As in the case of the diatomic molecules the refractivity is given by

$$\mu^2 - 1 = 4\pi\nu\left(\frac{A}{3} + \frac{2B}{3}\right) = R, \text{ say,}$$
$$= \tfrac{1}{3} \frac{2R_1 + R_2 + 31/8\, R_1 R_2 k}{1 - R_1 k/8 - 2R_1 R_2 k^2} + \tfrac{2}{3} \cdot \frac{2R_1 + R_2 - 31/16\, R_1 R_2 k}{1 + R_1 k/16 - \frac{1}{2} R_1 R_2 k^2}, \quad (7)$$

and the optical anisotropy as we have previously defined is

$$A/B = \frac{2R_1 + R_2 + 31/8\, R_1 R_2 k}{1 - R_1 k/8 - 2R_1 R_2 k^2} \cdot \frac{1 + R_1 k/16 - \frac{1}{2} R_1 R_2 k^2}{2R_1 + R_2 - 31/16\, R_1 R_2 k}. \quad (8)$$

To calculate A/B, we require to know R_1, R_2 and k. We have no direct means of determining any of these quantities, but let us tentatively assume that the refractivities R_1 and R_2 appropriate to the nitrogen and oxygen atoms are the same as in the respective molecules of N_2 and O_2. The known

refractivity of N_2O will then enable us to calculate k from equation (7). The equation can be put in the form of a bi-quadratic :—

$$k^4 R\delta^2 - k^3(R\gamma\delta + \beta\delta) - k^2(5R\delta - 3\alpha\delta + 2R\gamma^2 + 2\beta\gamma) - k(2R\gamma - 2\alpha\gamma) + 4(R - \alpha) = 0,$$

where

$$\alpha = 2R_1 + R_2 \qquad \beta = 31/8\, R_1R_2$$

$$\gamma = R_1/8 \quad \text{and} \quad \delta = 2R_1R_2.$$

Taking $R = 10{\cdot}28 \times 10^{-4}$ (for $\lambda = 0{\cdot}480\,\mu$)

$R_1 = 2{\cdot}832 \times 10^{-4}$

and $R_2 = 2{\cdot}384 \times 10^{-4}$,

the equation becomes

$$1874k_1^4 - 492{\cdot}4k_1^3 - 389k_1^2 - 1{\cdot}58k_1 + 8{\cdot}928 = 0,$$

where

$$k_1 = k \times 10^{-4}.$$

The only root of this equation consistent with our physical assumptions is $k = 0{\cdot}1460 \times 10^4$, which leads to a value of $d = 1{\cdot}59 \times 10^{-8}$ cm.

From (8),

$$A/B = 2{\cdot}80,$$

and hence $r = 14{\cdot}1$ per cent., while the value experimentally obtained by Lord Rayleigh was 15·7 per cent. and that obtained by Raman and Rao was 14·3 per cent. Without laying too great stress on the numerical agreement, it seems to show that the general idea of the method is correct.

Carbon Dioxide.

We shall now take up the case of carbon dioxide. Since we have no direct means of determining the refractivity to be attributed to carbon in the molecule of carbon dioxide, we have to derive it from some other source. We may take the refractivity of carbon as derived from saturated organic compounds, but since it is likely that even there its value is likely to be influenced by the proximity of the neighbouring atoms, it is better to derive it from a source where the influence of the neighbouring atoms vanishes. In a crystal of diamond there is regular tetrahedral symmetry, and each carbon atom is bound by one electron each to its four nearest neighbours. We may adopt the value of the atomic refractivity of carbon in diamond for our present case, since here also all the four outer electrons of carbon are presumably bound up with the neighbouring oxygen atoms.

The refractive index of diamond for $0{\cdot}480\,\mu$ is $2{\cdot}4370$* and taking its density to be $3{\cdot}514$,

$$\frac{\mu_1^2 - 1}{\mu_1^2 + 2} \cdot \frac{M}{\rho} = 2{\cdot}124,$$

where M is the atomic weight of carbon and ρ is the density of diamond. The corresponding value of $\mu^2 - 1$ for free carbon atoms at 0° C and 76 cm. pressure is given by

$$2{\cdot}124 = \frac{\mu^2 - 1}{3} \cdot \frac{2{\cdot}016}{8{\cdot}987 \times 10^{-5}},$$

where $2{\cdot}016$ is the molecular weight and $8{\cdot}987 \times 10^{-5}$ is the density of hydrogen.

Hence $$R_2 = \mu^2 - 1 = 2{\cdot}841 \times 10^{-4}.$$

Using our previous value of R for the oxygen atom from its value in the oxygen molecule, and making use of equation (7), we obtain the appropriate biquadratic :—

$$1663k_1^4 - 392k_1^3 - 322k_1^2 - 0{\cdot}865k_1 + 5804 = 0, \quad \text{where } k_1 = k \times 10^{-4},$$

in which the refractive index of CO_2 at N.T.P. has been assumed to be $1{\cdot}000453$. The physically relevant root of the equation gives

$$k = 0{\cdot}1284 \times 10^4 \qquad d = 1{\cdot}66 \times 10^{-8} \text{ cm.},$$

and hence $$A/B = 2{\cdot}42.$$

The imperfection of polarisation in a direction transverse to the incident light comes out as $10{\cdot}8$ per cent., which may be compared with Rayleigh's experimental value $11{\cdot}7$ per cent., and Raman and Rao's value $10{\cdot}6$ per cent.

The distance between the optical centres of the two nitrogen atoms in nitrous oxide is thus $3{\cdot}18 \times 10^{-8}$ cm., and the corresponding distance between the centres of the two oxygen atoms in CO_2 is $3{\cdot}32 \times 10^{-8}$ cm. Viscosity measurements indicate that the mean free-path size of the two molecules N_2O and CO_2 is practically the same. Since the size of the nitrogen molecule is larger than that of the oxygen molecule, the increased distance between the atomic centres in CO_2 is compensated by the smaller size of the oxygen atoms.

Carbon Disulphide.

We may expect that carbon disulphide has a constitution similar to carbon dioxide, and if we know the atomic refractivity of sulphur, we can calculate

* Landolt-Börnstein, 'Tabellen' (Martens), 1923 Edition, p. 918.

the anisotropy of carbon disulphide, and hence the imperfection of polarisation of the transversely scattered light in its vapour. We may adopt the following empirical method of calculating the refractivity of sulphur. The refractivity of H_2S for $0{\cdot}486\,\mu$ is $13{\cdot}12 \times 10^{-4}$, and since the refractivity of hydrogen is small compared with that of sulphur, we may to a first approximation obtain the value for sulphur by subtracting the refractivity of H_2 from that of H_2S. We thus get $R = 10{\cdot}31 \times 10^{-4}$. Using the same value for the refractivity of carbon as in carbon dioxide,

$$R_2 = 2{\cdot}841 \times 10^{-4}.$$

We do not possess data for the refractivity of carbon disulphide vapour at wave-length $0{\cdot}486\,\mu$, but from its refractivity for $0{\cdot}589\,\mu$ and its dispersion in the liquid state, we can easily calculate $\mu^2 - 1$, for $0{\cdot}486\,\mu$. We thus get

$$R = 30{\cdot}70 \times 10^{-4}.$$

Making a similar calculation as in the two preceding cases,

$$k = 7{\cdot}18 \times 10^2 \quad \text{and} \quad d = 2{\cdot}02 \times 10^{-8} \text{ cm.},$$

and

$$A/B = 2{\cdot}61, \quad \text{and} \quad r = 12{\cdot}5 \text{ per cent.}$$

The imperfection of polarisation obtained photographically by Lord Rayleigh in his earlier work was 12 per cent., while that obtained visually by Ganesan at Calcutta was 16·7 per cent. The latter value is probably entitled to greater weight, as in this case the illumination of the vapour was limited to a time just sufficient for the observation to be taken, and thus the chance of formation of clouds was reduced to a minimum. The difference between the observed and calculated values is no doubt to be attributed to the uncertainty in the values of the atomic refractivity.

The general agreement, however, in the three cases investigated makes it fairly certain that a large part of the optical anisotropy of gaseous molecules arises from the mutual action of the atoms of the molecule. It is thus of great importance to extend the investigation to the case of other molecules, particularly in the organic region, where the influence of the structure of the molecule on the anisotropy stands out conspicuously.

Summary.

In the foregoing paper, the view is put forward that the optical anisotropy of gaseous molecules, as revealed by the polarisation of the light scattered from them, is due to the mutual action of the doublets induced by the incident light in the different atoms constituting the molecule. It is assumed that each atom by itself is isotropic.

From the known refractivity and polarisation of the scattered light in hydrogen, nitrogen and oxygen, the atomic refractivities and distances between the optical centres in the molecules are deduced. These distances are consistent with the size of atoms deduced from the kinetic theory.

The investigation is extended to the three triatomic gases, N_2O, CO_2 and CS_2, and an expression is deduced for the imperfection of polarisation of the transversely scattered light in terms of the atomic refractivities of the different atoms and the distances apart of the optical centres. The calculated values of the imperfection are in satisfactory agreement with experiment.

I have great pleasure in acknowledging my indebtedness to Prof. C. V. Raman, at whose suggestion the above work was taken up, for his kind interest and helpful advice.

The Structure of Molecules in Relation to their Optical Anisotropy.—Part II*—Benzene and Cyclohexane.*

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1. *Introduction.*

In Part I* the view was advanced that the optical anisotropy of the molecules of a gas which is evidenced by the depolarisation of the light scattered by it can to a large extent be attributed to the mutual influence of the doublets induced in the different atoms of the molecule by the electrical field of the incident radiation.

Assuming that each atom is isotropic, and assuming the refractivity and anisotropy of the molecules of hydrogen, oxygen and nitrogen, the atomic refractivity and the distance apart between the "optical centres" was calculated in these cases. Extending the treatment to the case of triatomic molecules with the three atoms in a straight line, and using the previously obtained values for the atomic refractivities of nitrogen and oxygen and the diamond value of the atomic refractivity of carbon, the optical anistropies of the gases N_2O, CO_2 and CS_2 were calculated. The corresponding values of the depolarisation of the transversely scattered light were found to be in fair agreement with experiment. In this paper the work is extended to the two organic molecules, benzene and cyclohexane.

2. *Polarisation of the Scattered Light in Benzene and Cyclohexane.*

The imperfection of polarisation of the transversely scattered light in benzene vapour has been recently measured by Raman and Rao† and by Ganesan.‡ Their values are 0·068 and 0·066 respectively. We shall adopt the average of these two values, 0·067. Ganesan has also made measurements on a few benzene derivatives with the following results :—

Toluene	0·064
m-Xylene	0·067
Chloro-Benzene	0·078
Bromo-benzene	0·078

* 'Roy. Soc. Proc.,' A, vol. 107, p. 684.
† 'Phil. Mag.,' vol. 46, p. 426 (1923).
‡ 'Phil. Mag.,' vol. 49, p. 1216 (1925).

Proc. Roy. Soc. A. 110, 123-133, 1926.

It is significant that the values do not differ much from each other, which shows that the major part of the anisotropy has its origin in the benzene structure.

No previous measurements on the depolarisation of the light scattered by cyclohexane vapour have been recorded. The author has recently measured its value, using sunlight for illumination, and found it to be 0·011. A simple glass apparatus was employed for the measurement, and as the apparatus has been found particularly convenient for work with vapours which require heating, and as only small quantities of the substances are required, it may be worth while to describe it briefly.

Two bulbs, A and B, were blown on a tube of clear glass of about 2 cm. internal diameter, particular care being taken to see that there were no streaks or uneven portions on the bottom of the bulb B. The purpose of the second bulb is to prevent light diffused from places on the walls of the first bulb A which are struck by the incident light from reaching the observing window. The stem of the tube was about 20 cm. in length, and its end was drawn out into a horn (fig. 1). After cleaning and drying, a small quantity of the pure liquid was introduced into the bulb, and after evacuation with a pump, the tube was sealed off. The bulb was painted over with black paint, except for two windows in A for the entry and exit of a narrow pencil of sunlight and a small rectangular window in the bottom of B for observation. The tube was mounted horizontally inside a big iron cross-tube blackened inside and provided with suitable diaphragms to shut out stray light, and the measurements of the depolarisation were made visually with a double image prism and nicol. Arrangements were made to heat up the tube to different temperatures by means of an electric current. When the measurements are made with a view to obtain the optical anisotropy of the molecule, it is important to keep the density of the vapour as low as possible. The temperature was usually kept below the boiling point of the liquid. Check measurements on the vapours of benzene and carbon disulphide gave values 0·066 and 0·143 against Ganesan's values 0·066 and 0·167.

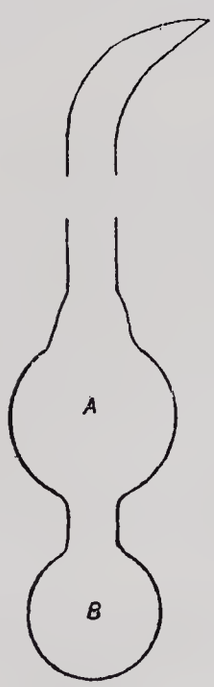

Fig. 1.

3. *Calculation of the Optical Anisotropy of Benzene.*

If A, B, C be the polarisations induced in a molecule when its three principal directions are respectively along the direction of an electric field of unit intensity

and of the frequency of the incident radiation, then the ratio of the weak component to the strong in the light scattered perpendicular to the incident beam is*

$$r = \frac{2(A^2 + B^2 + C^2) - 2(AB + BC + CA)}{4(A^2 + B^2 + C^2) + AB + BC + CA} \quad (1)$$

In the particular case when A = B, this becomes

$$r = \frac{2(A - C)^2}{9A^2 + 4C^2 + 2AC}.$$

In order to calculate the values of A, B and C for any molecule, it is necessary to assume some structure for it. In the case of benzene, chemical evidence requires that the six carbon atoms and the six hydrogen atoms are similar. From the further negative evidence that no optically-active derivative of benzene containing a single nucleus has been isolated, it has been held that the six carbon atoms lie in the same plane at the angular points of a regular hexagon,† and that the hydrogen atoms lie in the same plane at the six corners. On the other hand, if we proceed from the analogy of the crystal structures of naphthalene and anthracene as analysed by Sir W. H. Bragg,‡ the carbon atoms would be arranged in a puckered hexagonal ring as in diamond, the hydrogen atoms being joined to the carbons at the tetrahedral angle.

In order to decide which of these structures to adopt, a preliminary calculation was made in which the hydrogen atoms were ignored. The anisotropy of a structure consisting of six carbon atoms was calculated both when they are arranged in a plane ring as in graphite, and when they are arranged in a puckered ring as in diamond. In the former case, the distance between the centres of two neighbouring carbon atoms was assumed to be 1·45 A.U. and in the latter case 1·50 A.U. Calculations were made for two values of the atomic refractivity, viz., (1) the refractivity of carbon in diamond and (2) the refractivity usually ascribed to carbon in organic compounds.

The three principal directions in the molecule were taken to be (1) OX, parallel to 1–3 in fig. 2 ; (2) OY, perpendicular to 1–3 in the plane of the paper ; and (3) OZ, perpendicular both to 1–3 and to the plane of the paper. In the case of the puckered ring structure, the atom-centres 1, 3, 5 lie in the plane of the paper, while 2, 4, 6 lie 0·5 A.U. above this plane.

* Lord Rayleigh, 'Phil. Mag.,' vol. 35, p. 373 (1918).

† J. F. Thorpe, 'Chemistry in the Twentieth Century.'

‡ W. H. Bragg and W. L. Bragg, 'X-rays and Crystal Structure,' chap. XIV.

I. *Plane Ring of Six Carbon Atoms.*—When the field is parallel to the X-axis, the resultant electric intensity at each atom will be confined to the XY plane. The X-components of the polarisations of 1, 3, 4 and 6 will, by symmetry, be the same (fig. 3), say ex_1, and those of the atoms 2 and 5 will

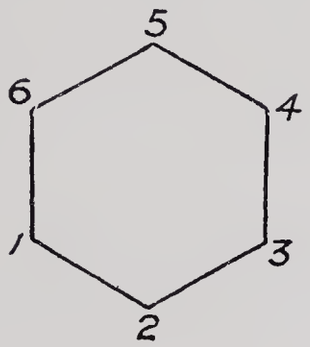

Fig. 2.

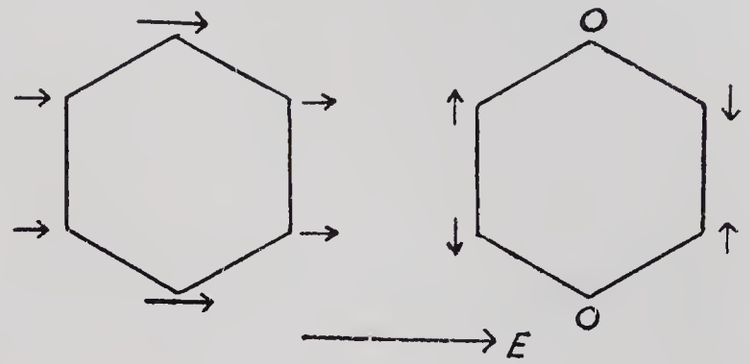

Fig. 3.

also be the same but have a different value, say ex_2. The y components of 2 and 5 will vanish, while those at 1, 3, 4 and 6 will be equal to each other, but alternate in sign.

The x-component of the electric intensity at any atom will be given by

$$\mathrm{E}' = \mathrm{E} + \Sigma \frac{3a^2 - r^2}{r^5} ex_n + \Sigma \frac{3ab}{r^5} . ey_n + \Sigma \frac{3ac}{r^5} ez_n, \qquad (2)$$

where E is the electric vector in the incident light ex_n, ey_n, ez_n are the components of the polarisation of any other atom in the molecule whose co-ordinates with respect to the atom we are considering are a, b, c, and r is the distance between the two atoms. The summation is extended to all the other atoms in the molecule.

The polarisation due to this field is given by

$$ex = e^2\lambda \mathrm{E}'$$

where $e^2\lambda$ is obtained from Lorentz's equation for the atomic refractivity

$$\frac{\mathrm{A}}{\rho} \frac{n^2-1}{n^2+2} = \frac{4\pi}{3} \mathrm{N}_0 e^2\lambda.$$

A is the atomic weight of the element, ρ is its density, n its refractive index, and N_0 the number of molecules in a gram-molecule.

Taking the atomic refractivity of diamond to be 2·124,* we get the value of $e^2\lambda$ for carbon to be $0{\cdot}836 \times 10^{-24}$, and calculating the field due to the other atoms, and summing them up with their proper signs, we obtain

* Part I.

$$1{\cdot}196\ ex_1 = \mathrm{E} \times 10^{-24} - 0{\cdot}151\ ex_1 + 0{\cdot}394\ ex_2 - 0{\cdot}0533\ ey_1$$

$$1{\cdot}196\ ex_2 = \mathrm{E} \times 10^{-24} + 0{\cdot}788\ ex_1 - 0{\cdot}041\ ex_2 - 0{\cdot}688\ ey_1$$

$$1{\cdot}196\ ey_1 = \qquad 0{\cdot}053\ ex_1 - 0{\cdot}344\ ex_2 - 0{\cdot}603\ ey_1.$$

Solving, we get

$$ex_1 = 1{\cdot}25\ \mathrm{E} \times 10^{-24}$$

$$ex_2 = 1{\cdot}77\ \mathrm{E} \times 10^{-24}$$

$$ey_1 = -\ 0{\cdot}30\ \mathrm{E} \times 10^{-24}.$$

The total polarisation parallel to the inducing field is $4ex_1 + 2ex_2$, which is equal to $8{\cdot}54\ \mathrm{E} \times 10^{-24}$.

When the field is parallel to OY, the same value of the polarisation is obtained. The molecule is thus isotropic in the XY plane.

When the field is parallel to OZ, the fields at any atom due to the other atoms oppose each other, thus producing a weaker resultant field and hence a smaller polarisation. Calculating as before, the induced moment of each atom in this case comes out to be $0{\cdot}495\ \mathrm{E} \times 10^{-24}$, and hence the total for the six atoms is $2{\cdot}97\ \mathrm{E} \times 10^{-24}$.

The optical anisotropy is thus A : B : C = 8·54 : 8·54 : 2·97 = 2·94 : 2·94 : 1, and the imperfection of polarisation of the transversely scattered light calculated according to (1) is 0·083.

If the refractivity of carbon is assumed to be that usually adopted in tables of refractivities, namely, 2·44 (for the F line), the polarisations parallel to the field when the field is along the X and Z axes respectively are found to be

$$\left.\begin{aligned} ex_1 &= 1{\cdot}58\ \mathrm{E} \times 10^{-24} \\ ex_2 &= 2{\cdot}34\ \mathrm{E} \times 10^{-24} \end{aligned}\right\}$$

and

$$ez_1 = 0{\cdot}534\ \mathrm{E} \times 10^{-24}$$

leading to a value of the anisotropy 3·4 : 3·4 : 1 and a depolarisation of the transversely scattered light of 0·10.

II. *Puckered Ring of Six Carbon Atoms.*—Assumed distance between the centres of two neighbouring carbon atoms = 1·50 A.U. Assumed atomic refractivity of carbon = 2·124.

Starting from the atom on the left-hand bottom corner, the co-ordinates of the centres of the different atoms are given below (see Table I).

Table 1.

	a.	*b.*	*c.*
1	0	0	0
2	1·225	−0·707	0·500
3	2·450	0	0
4	2·450	1·414	0·500
5	1·225	2·121	0
6	0	1·414	0·500

When the electric vector in the incident light is parallel to the X-axis, the directions of the X- and Y-components of polarisation will be as in figure 3, but

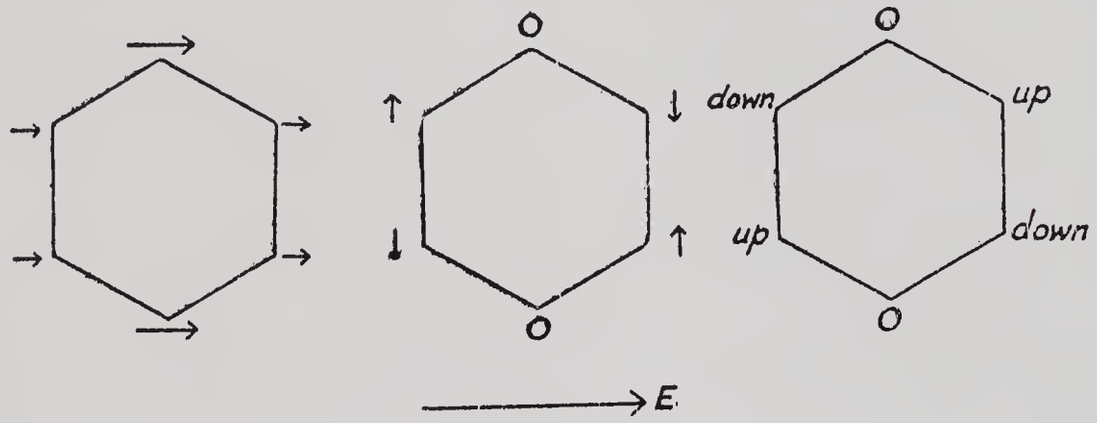

Fig. 4.

since the atoms are not confined to the XY-plane, the Z-components will not vanish. They will be as shown in fig. 4. We have therefore four unknowns to determine, namely, ex_1, ex_2, ey_1 and ez_1. The appropriate equations are found to be

$$1{\cdot}196\, ex_1 = \mathrm{E} \times 10^{-24} - 0{\cdot}110\, ez_1 + 0{\cdot}279 ex_2 + 0{\cdot}053 ey_1 + 0{\cdot}018 ez_1$$
$$1{\cdot}196 ex_2 = \mathrm{E} \times 10^{-24} + 0{\cdot}559 ex_1 - 0{\cdot}042 ex_2 - 0{\cdot}507 ey_1 + 0{\cdot}484 ez_1$$
$$1{\cdot}196 ey_1 = 0{\cdot}053 ex_1 - 0{\cdot}254 ex_2 - 0{\cdot}438 ey_1 - 0{\cdot}269 ez_1$$
$$1{\cdot}196 ez_1 = 0{\cdot}019 ex_1 + 0{\cdot}242 ex_2 - 0{\cdot}268 ey_1 + 0{\cdot}227 ez_1$$

which when solved give

$$ex_1 = 1{\cdot}11\ \mathrm{E} \times 10^{-24}$$
$$ex_2 = 1{\cdot}63\ \mathrm{E} \times 10^{-24}$$
$$ey_1 = -\,0{\cdot}301\ \mathrm{E} \times 10^{-24}$$
$$ez_1 = 0{\cdot}512\ \mathrm{E} \times 10^{-24}$$

The resultant polarisation is along the direction of the field and is given by $4ex_1 + 2ex_2 = 7{\cdot}70\ \mathrm{E} \times 10^{-24}$.

Writing down the appropriate equations when the incident field is parallel to the Z-axis and solving, we get for the total polarization parallel to the Z-axis $3 \cdot 68\,E \times 10^{-24}$. The resultant polarizations in other directions vanish.

The calculated value of r is 0·050.

If we take the atomic refractivity of carbon to be 2·44, we get A : B : C = 10·0 : 10·0 : 4·14 and $r = 0 \cdot 065$.

III. *Puckered Ring of Six Carbon Atoms with the Hydrogens introduced.*—In the calculations made above, we have altogether ignored the effect of the hydrogen atoms. Their introduction either in the plane of the carbon atoms in Case I or in the appropriate positions in the approximate plane of the puckered ring in Case II can only lead to an increase in the anisotropy. We have already found that if we adopt the plane ring structure, the calculated value of the anisotropy is too high even with the smaller value of the atomic refractivity. Unless therefore we assume that the distance between the optical centres is greater than 1·45 A.U., or that the atoms themselves are distinctly anisotropic with their axis of larger polarization perpendicular to the plane of the ring, we cannot explain the observed anisotropy of benzene with this structure. Since, however, the carbons are bounded on the outside by the hydrogens, it is unlikely that the distance between the optical centres of the carbons is really much greater than the X-ray distances. As for the second alternative, although it is quite likely that in a graphite structure, the atoms are more polarizable perpendicular to the plane than parallel to the plane, since we have nothing definite to go by, it is better for the present not to bring in an unknown factor in the shape of the anisotropy of the individual carbon atom. We shall therefore in what follows adopt the puckered ring structure of the carbon and work out the effect of introducing the hydrogens.

The question of the position of the hydrogen atoms is a difficult one. We shall assume that each hydrogen is joined to its carbon at the tetrahedral angle, the projection of the whole structure upon the average plane of the ring being the familiar graphic formula for benzene. In order to calculate the distance of a hydrogen atom from the centre of a neighbouring carbon atom, we cannot adopt the usual X-ray "diameter" of hydrogen, as in this case the hydrogen is not bounded by other atoms on the outside. In Part I, it was calculated that the distance between the optical centres in a hydrogen molecule is 1·37 A.U. Adding half this distance to the "radius" of a carbon atom, we obtain 1·43 A.U. to be the required distance. The atomic refractivity of hydrogen is assumed to be that calculated in Part I and the refractivity of carbon to be that of diamond.

The calculations were made exactly on the same lines as before, but since we have now to deal with the polarizations of twice as many atoms, we have twice as many unknowns. The appropriate equations for the polarizations of the different atoms were written down, and their solution was obtained by a method of successive approximations. Assuming the values of the polarization of the carbon atoms obtained above when the hydrogens were not present, the polarizations of the hydrogens were calculated neglecting the small influence of the other hydrogen atoms. These were substituted in the equations for the polarization of the carbon atoms, and their solution gave a better approximation to the true values. The operation was repeated a few times until further approximations did not cause any appreciable alteration in the values.

When the field is parallel to the X-axis, the following values were obtained for the polarizations parallel to the field.

$$ex_1 = 1{\cdot}53 \text{ Ex } 10^{-24}$$
$$ex_2 = 1{\cdot}98 \text{ Ex } 10^{-24}$$
$$ex_1' = 0{\cdot}64 \text{ Ex } 10^{-24}$$
$$ex_2' = 0{\cdot}11 \text{ Ex } 10^{-24}$$

where ex_1', ex_2' refer to the hydrogen atoms. The resultant polarization parallel to the X-axis is $4\,(ex_1 + ex_1') + 2\,(ex_2 + ex_2')$, *i.e.*, $12{\cdot}86\ \mathrm{E} \times 10^{-24}$.

With the field parallel to the Z-axis, the polarizations of the carbon and hydrogen atoms parallel to the field were

$$ez_1 = 0{\cdot}52\ \mathrm{E} \times 10^{-24}$$
$$ez_1' = 0{\cdot}29_5\ \mathrm{E} \times 10^{-24}$$

and thus we get for the resultant polarization $6\,(ez_1 + ez')$ the value $4{\cdot}88\ \mathrm{E} \times 10^{-24}$.

The polarization when the field is parallel to the Y-axis would be the same as when it is parallel to the X-axis.

The calculated value of the depolarization of the transversely scattered light is 0·074, which may be compared with the experimental value 0·067.

4. *The Molecular Refractivity of Benzene.*

The mean polarization per unit field averaged over all orientations is $(\mathrm{A} + \mathrm{B} + \mathrm{C})/3$. With the values obtained in the last section, its value is $10{\cdot}2 \times 10^{-24}$. Calculating the molecular refractivity by means of the formula

$$\frac{\mathrm{M}}{\rho}\,\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi}{3}\,\mathrm{N}_0\,\frac{\mathrm{A} + \mathrm{B} + \mathrm{C}}{3},$$

we find its value to be 25·9 (for the F line). The experimental value of the

molecular refractivity of benzene* is 26·2 for the D line and 26·7 for the F line. The difference is not large considering the nature of the assumptions involved in the calculations. It may be recalled that the atomic refractivities of carbon and hydrogen which we have used are not the refractivities deduced from the molecular refractivities of organic compounds by the rule of additivity. Such values are likely to be invariably higher owing to the influence of the other atoms in the molecule. If we adopt a plane structure, both the refractivity and the anisotropy are found to be too high.

5. *Optical Anisotropy and Refractivity of Cyclohexane* (C_6H_{12}).

Compared with benzene, cyclohexane has a small anisotropy; while the depolarization of the transversely scattered light in the former is 0·067, that in the latter is only 0·011. The extra hydrogen atoms should therefore occupy such positions as will reduce the anisotropy. If we retain the idea that the binding of one carbon atom to another and of a hydrogen to a carbon take place at the tetrahedral angle, the structure of cyclohexane can be derived from that of benzene by adding a hydrogen to each carbon atom, the extra hydrogens being alternately below and above the plane of the paper in fig. 2. The new hydrogens attached to carbon atoms 1, 3 and 5 will be vertically below the plane of the paper, while those attached to 2, 4 and 6 will be vertically above the plane. We assume that the distance of the optical centres of these hydrogen atoms from the centres of the neighbouring carbon atoms to be the same as before, namely 1·43 A.U. We can now calculate the optical anisotropy of such a structure. When the field is parallel to the X- or Y-axis, the polarization of the extra hydrogens (which we shall denote by ex_1'', ex_2'', etc.) will cause a field at the carbons tending to reduce their polarization, and the polarization of the carbons will similarly tend to reduce the field at the hydrogens while when the field is parallel to the Z-axis, the polarizations will help each other. Using the same method of successive approximations, and neglecting the mutual influence of the previous set of hydrogen atoms on the new set, the following values are obtained for the polarisations parallel to the field:

$$ex_1 = 1{\cdot}47 \quad \mathrm{E} \times 10^{-24}$$
$$ex_2 = 1{\cdot}90 \quad \mathrm{E} \times 10^{-24}$$
$$ex_1' = 0{\cdot}63 \quad \mathrm{E} \times 10^{-24}$$
$$ex_2' = 0{\cdot}12 \quad \mathrm{E} \times 10^{-24}$$
$$ex_1'' = 0{\cdot}15 \quad \mathrm{E} \times 10^{-24}$$
$$ex_2'' = 0{\cdot}09 \quad \mathrm{E} \times 10^{-24}$$

* 'Landolt Bornstein Tabellen,' p. 977.

Therefore, total polarization parallel to the X-axis $= 13{\cdot}2\ \mathrm{E} \times 10^{-24}$, and

$$ez_1 = 0{\cdot}86\ \mathrm{E} \times 10^{-24}$$
$$ez_1' = 0{\cdot}21\ \mathrm{E} \times 10^{-24}$$
$$ez_1'' = 0{\cdot}63\ \mathrm{E} \times 10^{-24}$$

Therefore, total polarization parallel to the Z-axis $= 10{\cdot}2\ \mathrm{E} \times 10^{-24}$.

From the similarity to the case of benzene, the polarization parallel to the Y-axis will be the same as that parallel to the X-axis, and hence the value of the anisotropy is 13·2 : 13·2 : 10·2. The calculated value of r is 0·008.

The average polarization obtained from the above data is $12{\cdot}2\ \mathrm{E} \times 10^{-24}$ and the calculated molecular refractivity 31·0, while the observed refractivity is 29·7 for the D line and 30·1 for the F line. The difference is not large considering the somewhat arbitrary way in which we fixed the atomic refractivities.

One noteworthy feature of the optical anisotropies of individual molecules is the high values of their double refraction compared with those of crystals. For example, potassium nitrate, which is a strongly doubly-refracting crystal, has for the ratio of its principal refractive indices the value 1·587 : 1·336, *i.e.*, 1·19 : 1, while a benzene molecule, which is also an example of a molecule with fairly high anisotropy, has for its corresponding ratio the value 2·45 : 1. The enormous decrease in the value of the anisotropy when the molecules get arranged into a crystal is due to the influence of the polarization of the atoms in the neighbouring molecules, which, being arranged on all sides of the molecule under consideration, tend to make its polarization more isotropic. A similar instance is furnished by the change in passing from benzene to cyclohexane.

6. *Summary.*

Developing the idea put forward in Part I that the optical anisotropy of gaseous molecules which is responsible for the partial depolarization of the light scattered in a direction perpendicular to the incident beam, can be explained to a large extent by the mutual influence of the electrical doublets induced in the different atoms of the molecule by the electric field of the incident radiation, the optical anisotropy of benzene has been calculated for two different structures. Each atom is assumed to be isotropic. If the six carbon atoms are assumed to lie in a plane with their centres at the corners of a regular hexagon, as in graphite, the optical anisotropy comes out too high even when the hydrogens are ignored. If, on the other hand, the carbon atoms are arranged in a puckered ring, as in diamond, and the hydrogens are joined to the carbons

at the tetrahedral angle, the calculated and observed values of the optical anisotropy agree well, when the atomic refractivity of carbon is assumed to be that of diamond and the atomic refractivity of hydrogen to be that in gaseous hydrogen. The calculated and observed values of the molecular refractivity also show good agreement.

The calculation is extended to cyc ohexane. The six extra hydrogen atoms are supposed to be attached to the carbon atoms alternately on each side of the approximate plane of the carbon ring. The calculation shows that a considerable falling off in anisotropy is to be expected, which is borne out by experiment. The calculated refractivity is also in fair agreement with the experimental value.

A simple glass apparatus is described for the measurement of the imperfection of polarization of the light scattered by vapours which require heating for their production.

I am very thankful to Prof. C. V. Raman for his kind and encouraging interest in the work.

XXXIX. *The Optical Anisotropy of some simple Inorganic Gaseous Compounds.*

By K. R. Ramanathan, *M.A., D.Sc., and* N. G. Srinivasan, *B.Sc., Physics Department, University College, Rangoon* *

Introduction.

FROM the time that Lord Rayleigh discovered the imperfection of polarization of the transversely scattered light in gases, it has been the hope of physicists that some time or other it would lead to important knowledge regarding the structure of atoms and molecules. In his recent work on the doubly refracting properties of typical inorganic crystals, W. L Bragg † has made use of the idea of the mutual influence of the polarization of the different atoms of the crystals, and has deduced results which are in general agreement with observation. In this work, Bragg assumes with Wasastjerna that the atoms are in an ionized condition : that is, they have given up or taken in a sufficient number of electrons so that the electronic structure of each ion approaches closely that of the nearest inert gas. He further assumes that each ion by itself can be considered optically isotropic.

One of the authors has recently shown that the optical anisotropy of some of the common inorganic gases ‡ which is evidenced by the imperfection of polarization of the transversely scattered light in these gases, can be likewise explained if we take into account the mutual influence of the

* Communicated by the Authors.
† Proc. Roy. Soc. A, vol. cv. p. 370 (1924).
‡ Proc. Roy. Soc. A, vol. cvii. p. 684 (1925).

Phil. Mag. 1, Seventh series, 491–496, 1926.

polarizations of the different atoms in the molecule. The work has later been extended to the organic molecules benzene and cyclohexane, but in all the cases that have been hitherto examined the gases are of the "homo-polar" or shared-electron type.

With a view to getting some idea of the optical anistropy of the "hetero-polar" molecules, experiments have been made on a few simple hydrides. The inert gases are known to possess a high degree of symmetry, and the experiments of Lord Rayleigh * on argon and of Capannes and Lépape on xenon and krypton † show that the optical anistropies of these molecules are very small, the values of the imperfection of polarization of the transversely scattered light in these gases being respectively ·0046, ·0055, and ·0055. Hydrides of elements adjoining the inert gases, like those of the halogens, would, it is believed, assume electronic structures similar to those of the inert gases, with perhaps a slight deformation of the symmetrical structure caused by the presence of the hydrogen nuclei. The gases CH_4, NH_3, H_2O may be expected to approach neon, while SiH_4, PH_3, H_2S, and HCl would approach argon.

In the following paper the results obtained with ammonia, sulphuretted hydrogen, and hydrochloric acid are described and discussed.

Experimental.

The apparatus employed was of the usual type, being a rectangular metal cross-tube of 5 cm. internal diameter. Each arm of the cross was 27 cm. in length. The tube was coated inside with black enamel which on heating gave a hard glassy coating. Three ends of the cross were closed with plane glass plates sealed on with sealing-wax or hard paraffin, while the fourth end was closed with a metal cap. An oblique metal plate with a uniform glassy coating of black enamel was placed near the closed end so as to reflect away any stray light which might reach that end. Suitable blackened metallic apertures were placed in the different arms so as to shut out stray light. The cross was also provided with two side tubes, one to serve as an inlet for the gas and the other to serve as an exit.

After drying and cleaning, the apparatus was exhausted by means of a pump and the dry dust-free gas was slowly let in. During the experiment a continuous stream of the

* Proc. Roy. Soc. A, vol. xcviii. p. 57 (1920).
† *Comptes Rendus*, clxxix. p. 325 (1924).

gas was kept running. The measurements of depolarization were made in the usual manner by means of a Wollaston double-image prism of quartz and square-ended nicol with a small low-power reading telescope placed behind the nicol.

The pure gases were prepared in the following manner :—

(a) *Hydrochloric acid gas.*

By the action of strong sulphuric acid on sodium chloride. The gas was dried by passing over fresh phosphorus pentoxide.

(b) *Hydrogen sulphide.*

By heating antimony trisulphide with concentrated hydrochloric acid. It was found that free evolution of gas was helped by mixing the antimony sulphide with clean sand. The gas was first bubbled through water to remove the acid spray and then dried over phosphorus pentoxide.

(c) *Ammonia.*

By warming a concentrated solution of ammonia. The gas was passed through a lime tower to remove moisture.

Usually for observations on the scattering of light in gases, the dust particles that are invariably present are removed by slow passage through a tube packed with cotton-wool. As it was, however, found that cotton-wool was slowly attacked by HCl, it was replaced throughout the experiments by clean dry asbestos wool, which was found to be a good substitute.

Error due to convergence of the Incident Rays.

Before discussing the experimental results, it is worth while to consider a source of error which, while unimportant when measuring the imperfection of strongly depolarizing substances, becomes of considerable importance when small values of depolarization are measured *. When the incident beam is focussed by means of a lens, and the imperfection of polarization is measured in a direction perpendicular to the average direction of the beam, the value obtained would be different from what it would be if the beam were strictly parallel. The error would be greater the greater the convergence of the beam. To find its amount, consider a beam of plane polarized light with its electric vector parallel to OZ moving along the X-axis. When observed along OY, let the Z-component of the intensity of the scattered light be A and the X-component B ; then, when the incident light

* Lord Rayleigh, Proc. Roy. Soc. A, vol. xcv. p. 161.

is unpolarized, the components will be A + B and 2B respectively. If the direction of observation be changed by an angle θ, the principal components in a plane perpendicular to the scattered ray will become A + B and B $(1 + \cos^2\theta)$ + A $\sin^2\theta$ respectively, and thus the observed ratio of the weak component to the strong will be

$$\rho_\theta = \frac{A\sin^2\theta + B(1+\cos^2\theta)}{A+B} = \frac{2B + (A-B)\sin^2\theta}{A+B},$$

which differs from ρ, the value in a transverse direction, by $(A-B)\sin^2\theta/(A+B)$.

In our present case, $\sin\theta$ varies from $-a/d$ to a/d where $2a$ is the aperture of the lens, and d is the distance from the lens at which the rays are focussed *.

We have, therefore, to find the average values of ρ_θ when θ varies through this range. A simple integration and averaging give for the ratio of the weak component to the strong in a direction perpendicular to the average direction of the beam

$$\frac{H}{V} = \frac{2B + (A-B)\sin^2\theta/2}{A+B}.$$

In the case of a gas producing an imperfection of polarization of 0·01 in a strictly perpendicular direction, the error caused by the non-parallelism of the incident rays will be as much as ·0038 when θ is 5° and ·0014 when θ is 3°.

Similar errors will be caused by a wrong adjustment of the double-image prism and by the direction of observation not being exactly perpendicular to the incident beam. The former error can be avoided by a careful adjustment of the double-image prism; the latter is usually small in visual observations, but it is one to be borne in mind when measurements are made photographically where the temptation is to use a large aperture in order to secure economy of light.

Results.

The observed value of the ratio of the weak component to the strong in the transversely scattered light in each of the gases HCl, H_2S, and NH_3 was found to be the same, namely ·010. The measurements were repeated on different days, and consistent results were obtained. There was no evidence of fog formation in any of the cases. In changing from one gas to another the whole apparatus was overhauled and

* With the small angles usually employed, the distinction between $\sin\theta$ and $\tan\theta$ may be dropped.

thoroughly cleaned, and the inside of the tube was repainted. The maximum angular divergence of the rays from the axis was measured to be 3°·8, and hence the error due to the non-parallelism of the incident rays was ·002. If we subtract this from the value obtained above, we get for all the three gases the corrected value ·008.

It is remarkable that the values of ρ for all these gases should be so low, and that they should all be equal to each other. They are also of the same order of quantities as the values obtained for the inert gases. As mentioned above, Lord Rayleigh obtained the value ·0046 for argon, which, however, has not been corrected for the non-parallelism of the incident rays. Lord Rayleigh estimated the extreme divergence of the incident rays from the axis to lie between 3° and 4°, and the angle subtended by the aperture of the camera was of the same order. The corrected value would be only about ·0025. Whether this residual effect does exist or not is worth re-examination.

It is now generally believed that in hydrochloric acid gas the electron belonging to the hydrogen atom has gone over to the chlorine atom to form one of its outermost orbits, thus completing the argon configuration, and similarly in sulphuretted hydrogen the two electrons from the hydrogen atoms have been transferred to the outermost orbits of sulphur. The smallness of depolarization of these gases supports this view. Likewise in ammonia, the additional electrons belonging to the three hydrogen atoms may be looked upon as having been transferred to the nitrogen to complete the neon configuration. Although no measurement of the depolarization of the transversely scattered light in neon are available, it may be expected to be small.

The cases of carbon monoxide and nitrogen are interesting. Langmuir and others have suggested that the configurations of the outer electrons of these gases are similar. If that is so, we expect that the optical anisotropies of the two gases should be nearly the same. Visual measurements made with sunlight at Calcutta show that carbon monoxide shows a depolarization of 3·4 per cent., while for nitrogen Lord Rayleigh * obtained the value 4·06 per cent. by the photographic method. On the other hand, if we calculate the depolarization of nitrogen from the visual measurements of Raman and Rao † on air (4·37) and oxygen (8·4), we obtain the value 3·5 per cent. For purposes of comparison

* Proc. Roy. Soc. A, vol. xcvii. p. 435 (1920).
† Phil. Mag. vol. xlvi. p. 427 (1923).

it is better to choose the values obtained by the same method, and the closeness of the values obtained by the visual method is very striking.

Summary.

In the foregoing paper, measurements of the depolarization of the light scattered by the gases hydrogen chloride, sulphuretted hydrogen, and ammonia are described, and the results obtained are discussed in their relation to the structure of the molecules. The depolarization in a direction perpendicular to the incident beam was in all cases the same, namely ·008, indicating a high degree of optical symmetry. The value of the anisotropy supports the view that in these gases the electrons belonging to the hydrogens have gone over to the outer orbits of the heavier atoms, in order to complete the electronic structure characteristic of the nearest inert gas. It is also pointed out that the values of the depolarization of nitrogen and carbon monoxide, both obtained visually, have practically the same value, supporting the view that the configurations of the outer electrons of these molecules are similar. The error caused in the measurement of the depolarization of the light scattered by substances owing to the non-parallelism of the incident light is discussed.

1

The Polarisation of the Light scattered by some Organic Vapours.

BY

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Introduction.

In two recent papers,[1] one of the authors has developed an approximate theory of the optical anisotropy of molecules which has been found helpful in explaining the broader features of its dependence on molecular structure. For further progress, it was felt desirable to secure more data regarding the polarisation of light scattered by vapours of substances whose molecular structures are known from other considerations and the experiments described in this paper were undertaken with that view. An extensive series of measurements on the polarisation of the light scattered by organic vapours has been recently published by A. S. Ganesan,[2] and another series both as regards intensity and polarisation on methane and some of its homologues by Cabannes and Gauzit.[3] Most of the substances studied by us differ, however, from those of the above two investigations and the apparatus employed also possesses some features of interest, having been designed for work with vapours which require heating for their production. In this paper, we have given a brief account of our experiments followed by a discussion of the results

[1] 'The Structure of Molecules in relation to their Optical Anisotropy.' Part I, Proc. Roy. Soc. A, Vol. 107, p. 684; Part II in course of publication.

[2] Phil. Mag. Vol. XLIX, June 1925, p. 1216.

[3] Journ de Physique, Ser. VI, Tome VI, pp. 182-198 (June 1925).

Proc. Ind. Assn. Cult. Sci. 9, 203-209, 1925-26.

obtained and of some points connected with the measurement of depolarisation in gases and vapours; the optical anisotropy of the carbon atom and its significance are also considered.

Apparatus.

The main part of the apparatus consisted of a double-bulbed (diameter of bulbs 5 to 6 cms.) glass tube of the form shown in the figure (Fig. 1).[1] Particular care was taken to see that the smaller bulb was blown clear and uniform with no blob or streak at its bottom. After cleaning and drying, a small quantity of the pure substance was introduced into the tube and, after pumping out the air inside, the horn end of the tube was sealed off. The bulbs and tube were painted black leaving only three small windows, two at the sides of the larger bulb for the entrance and exit of the incident light and the third at the bottom of the smaller one for the observation of the scattered track, the stem of the tube serving as a background. Experiments with a glass cross-tube of the kind used by Cabannes and his co-workers showed that it was difficult to secure anything like the satisfactory background obtained with metal tubes fitted with diaphragms. Since the introduction of metal diaphragms inside the glass cross would lead to the presence of undesirable impurities especially when organic vapours at higher temperatures were being studied, the expedient of a double bulb was adopted, the constriction between the bulbs serving as a sort

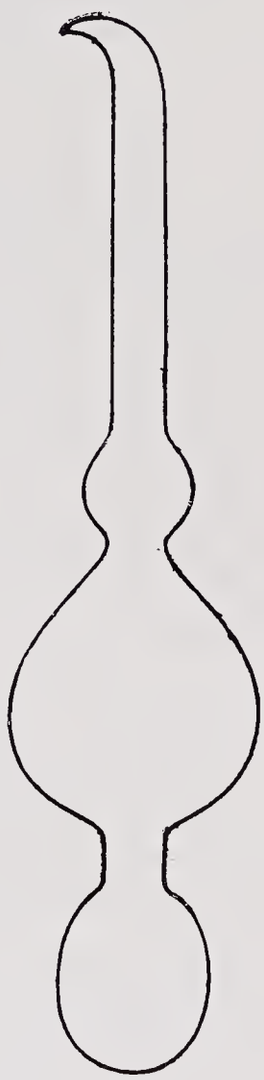

Fig. 1.

[1] The measurements on phenol and the following aromatic compounds were made with bulbs of smaller diameter (about 4 cm.).

of diaphragm, another diaphragm being provided by the slit in the black paint at the bottom of the smaller bulb.

The tube was mounted horizontally inside a thick iron cross tube so that the bigger bulb was at its centre. The cross was thoroughly blackened inside and provided with suitable diaphragms for shutting out stray light and arrangements were made for heating the cross electrically. The background end of the cross tube was closed by a blackened metal cap and the other ends were provided with glass windows.

Sunlight was concentrated by means of a lens at the centre of the bigger bulb and the polarisation in a direction perpendicular to the incident beam was measured in the usual manner with a double image prism and square-ended nicol. The maximum deviation of the incident rays from the axis was not more than 3° or 4° and no correction was made for this deviation. The temperature of the cross was usually kept not far from the boiling point of the substance. The following table gives the values of the depolarisation of the transversely scattered light for the substances studied.

TABLE I.

Substance.	Temperature.	$\frac{\text{Intensity of weak component}}{\text{Intensity of strong component.}} \times 100$	
Carbon disulphide ...	40°C	14·3	16·7 (Ganesan) 12·0 (Raman and Rao).
Hexane	60°	2·1	3·3 (Ganesan) 1·5 (Cabannes and Gauzit).
Cyclo-hexane	60°	1·0	

TABLE I—*contd.*

Substance.	Temperature.	Intensity of weak component / Intensity of strong component. × 100	
Benzene	60°C	6·6	6·6 (Ganesan) 6·8 (Raman and Rao).
Phenol	205°	6·1	
Nitro-benzene	,,	5·6	
Aniline	,,	4·9	
Benzoic Acid	,,	5·3	
Salicylic Acid	,,	5·3	
Naphthalene	250°	7·9	
Ethyl Bromide	90°	3·2	
Ethylene Bromide ...	110°	6·7	

The results of measurements by previous investigators are given in columm 4.

Discussion.

It will be noticed that the values of the depolarisation for the single-ring aromatic compounds show significant variations among themselves. Aniline has thus a distinctly lower value than benzene showing that the substitution of H by NH_2 reduces the optical anisotropy, which can be explained if the polarisation of the NH_2 group is greater when the incident field is perpendicular to the " plane" of the benzene ring than when it is parallel to it. The same is true of the COOH group in benzoic and salicylic acids. Sir W. H. Bragg's analysis of the structure of benzoic acid crystals shows that the COOH groups of two neighbouring layers of molecules are turned towards each other and lie across the plane of

cleavage. Ganesan has found that the values of the depolarisation for chloro-and bromo-benzene are each ·078, thus higher than that of benzene. This is just what we should expect in view of the larger refractivities of chlorine and bromine atoms. Naphthalene again has a larger anisotropy than benzene which is in consonance with its double-ringed structure with two benzene rings placed side by side. The compounds ethyl bromide and ethylene bromide with ethane and ethyl alcohol form an interesting series. The values of depolarisation are as follow :—

Ethane ...	...	·016	Cabannes and Gauzit.
Ethyl alcohol ...	...	·017	Ganesan.
Ethyl Bromide ...	...	·032	Table I.
Ethylene Bromide	...	·067	

The substitution of H or OH by the highly refracting bromine atom at the end of the molecule increases the influence of the polarisation of this atom on the other atoms and thus increases the anisotropy. If both the end atoms are replaced by bromine, the effect is accentuated. Krishnan [1] has obtained the same general variations with these substances in the liquid condition and also found that the corresponding chlorides show the same effect but to a smaller degree than the bromides.

Experimental Results of Cabannes and his Co-workers.

One disconcerting feature about the measurements of the depolarisation of light scattered by gases and vapours is the uniformly lower values obtained by Cabannes and his co-workers. The French investigators used a glass cross for their work and took great care in purifying their material. They think that the higher values obtained by other workers may be due to the presence of a trace of some impurity perhaps given out by the black paint used for blackening the insides of the metal crosses. From our experience, we are

[1] Phil. Mag., Vol. L, p. 697 (1925).

inclined to consider it possible that the lower values obtained by Cabannes and his co-workers may have been due to an imperfect background. The inside diameter of their glass crosses was three centimeters and no diaphragms were used for shutting out stray light. It might be thought that an unpolarised background illumination would affect both the components alike and would thus be of little importance, but it is not so. When we adjust the nicol so as to secure equality of brightness of the two tracks produced by the double image prism, its position is such as to cut off most of the illumination in the background of the brighter component and to transmit a considerable part of the illumination in that of the weaker component. The contrast between the track and its background is thus greater in the former case than in the latter, and our tendency either when viewing the tracks visually or when judging the density of photographic images is to overestimate the brightness of the track with the darker background; or in other words, when we think that the two tracks have been adjusted to be of equal brightness, the primary component is really weaker and the estimated value of the depolarisation smaller. For the same background illumination, the percentage error would be greater, the weaker the depolarisation of the scattered light. However, the possibility of the admixture of a small quantity of foreign matter is one to be kept in mind. It would be worth while to obtain careful measurements for a few substances having small values of depolarisation using a glass cross of larger dimensions than that used by Cabannes and his co-workers and provided with proper apertures for shutting out stray light.

Optical Anisotropy of the Carbon Atom.

Ganesan's measurement on the depolarisation of the light scattered by CCl_4 vapour (·019), Krishnan's measurement on CCl_4 liquid (·061) and Cabannes and Gauzit's on CH_4 gas

(·015) show definitely that we must assume a certain anisotropy of structure even in these molecules and since the four atoms attached to the central carbon atom are identical, an anisotropy of the carbon atom itself. Cabannes and Gauzit have discussed this point in their paper with reference to CH_4 and they conclude that the carbon atom cannot possess regular tetrahedral symmetry. In this connection, it may be pointed out that according to Bohr's theory, the four outer electrons of the carbon atom, although they would possess considerable symmetry, cannot possess perfectly regular tetrahedral symmetry as their orbits are partly determined by the presence of the two internal electrons describing circular orbits whose planes are at an angle of 120° with each other. The anisotropy of the internal orbits must be reflected in the orbits of the outer electrons and the latter cannot therefore possess *perfect* symmetry. An extension of the argument shows that we must expect a certain amount of anisotropy even in the atoms of the inert gases, and the anisotropy of helium should be particularly marked. The only measurement of the depolarisation of this gas is that made by Lord Rayleigh who fixed an upper limit to its value at 6·5 per cent. An exact measurement of the depolarisation of helium is very much to be desired.

Intensity and Polarisation of Skylight at Sunrise and Sunset.

IT is now well-established that the illumination of the clear day-sky at high-level stations is almost entirely due to molecular scattering by the atmosphere. The remarkable changes in the character of sky-illumination which take place when the sun approaches and gets below the horizon have been the subjects of study of a number of investigators and in recent years, particularly of Profs. Dorno[1] and Gruner.[2] Some of the phenomena, as for example, the changes of colour and polarisation of skylight and the appearance of the earth-shadow, occur in the clearest of weathers and at such high-level stations that their origin cannot be attributed to anything other than molecular scattering. Gruner has, indeed, shown that the observed changes of colour of skylight when the sun is near the horizon can be explained by scattering by a pure atmosphere.

The writer has recently calculated the intensities of sky illumination due to molecular scattering when the sun is on the horizon at a place 2 km. above sea-level for the wave-lengths 0·45 μ, 0·55 μ, and 0·65 μ by a method somewhat different from that of Gruner, and as some of the results obtained are new, they may be of general interest. The light from the sky when the sun is on the horizon has a much smaller proportion of the shorter waves than the normal daylight sky. In the zenith, where the relative proportion of the short waves is the largest, the ratio of blue (0·45 μ) to red is only 1·3 while, according to the inverse fourth-power law, it would be 4·3. As we move from the zenith to the horizon, the proportion of blue decreases still more, the ratio becoming 0·48 at a zenith distance of 80° in a direction perpendicular to the sun's rays, and 0·45 at the same zenith distance on the side opposite to the sun. The calculated absolute values of intensity are also of the same order of quantities as the values observed by Dorno at Davos (1·6 km. above sea-level), but there is a tendency for the observed values to be larger in the quadrant of the sky containing the sun.

The way in which different layers of the atmosphere contribute to the illumination is also interesting. The proportions of the total light of wave-lengths 0·45 μ and 0·65 μ coming from different layers of the zenith sky are as follow:

Height.	Wave-length.	
	0·45 μ.	0·65 μ.
2-10 km. . . .	8 per cent.	38 per cent.
10-20 ,, . . .	47 ,,	44 ,,
20-30 ,, . . .	33 ,,	15 ,,
30-50 ,, . . .	12 ,,	4 ,,

The single kilometre layers from which the maximum percentages come are 17 to 18 km. for the shorter wave and 9·5 to 10·5 km. for the longer.

In the calculations mentioned above, only primary scattering has been taken into account. But observation shows that complete neglect of self-illumination is not justifiable. For example, even in the clearest weather during the winter months at Simla (1·9 km. above sea-level), when the light from the zenith sky is analysed by a double-image prism and nicol, the weaker component is found to be richer in blue than the stronger, due, no doubt, to the self-illumination being greater for the shorter waves.

The effect of self-illumination may be expected to be a minimum, if confining our attention to the longer

[1] C. Dorno, "Himmelshelligkeit, Himmelspolarisation und Sonnenintensität in Davos, 1911 bis 1918," *Veröffent. des Prüssischen Meteor. Instituts, Abhandlungen*, Bd. 6, 1919.

[2] P. Gruner, "Beiträge zur Physik der freien Atmosphäre," Bd. 8, pp. 1 and 120 (1919).

Nature 118, 337–338, 1926.

waves, we observe in a direction perpendicular to the sun's rays but at a zenith distance of 70° to 80°, where the absolute intensity of the primarily scattered longer waves is greater and the greater part of the radiation comes from a comparatively thinner layer nearer the surface of the earth. Observations at Simla show that the polarisation for the red in these directions often reaches values so high as 30 per cent., which may be compared with 91·6 per cent., the value of the polarisation of the light transversely scattered by pure air.

K. R. RAMANATHAN.

Colaba, Bombay, June 25.

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On Fluctuations of Dielectric Constant in Liquids and Theories of Molecular Scattering of Light.

BY

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I. Introduction.

In two previous papers,[1] the electromagnetic theory of the scattering of light in fluids was dealt with by the present writer from the molecular point of view. Einstein's expression for scattering was derived for liquids composed of isotropic molecules; for liquids composed of anisotropic molecules, it was shown that just as in the case of gases, there would in addition be an unpolarised scattering and expressions for the intensity and polarisation of the scattered light were derived. Gans[2] has, in the meanwhile, developed the phenomenological theory so as to include the case when the transversely scattered light is partially polarised by assuming that the fluctuations of dielectric constant which on Einstein's theory are responsible for the scattering of light, are in general anisotropic, these deviations from isotropy being also responsible for the phenomenon of electric double refraction. Some differences between the expressions for scattering put forward by Gans, by L. V. King[3] and by the present writer have shown the necessity for a re-examination of the question of fluctuations of dielectric constant in a liquid.

[1] K. R. Ramanathan, Proc. Ind. Assoc. for Cult. of Science, Vol. VIII, Part I, pp. 1-22 and Vol. VIII, Part III, pp. 181-198 (1923). These will be referred to in the sequel as papers A and B respectively.

[2] R. Gans, Zeit. für Physik, xvii, p. 353 (1923).

[3] L V. King; Nature, cxi, p. 667 (1923). See also paper B.

Ind. Journ. Phys. 1, 413-436, 1926-27.

2. *Fluctuations of dielectric constant in a small volume element.*

The relation between the dielectric constant and the molecular density and polarisability which is usually used in deriving the fluctuations of dielectric constant in a liquid, is the Lorentz-Mosotti formula

$$\frac{K-1}{K+2}=\frac{4\pi}{3}nA' \qquad \ldots \quad (1)$$

where K is the dielectric constant of the liquid, n is the mean density of the molecules contained in it and A′ the average polarisability of the molecules. By differentiation,

$$dK=\frac{(K-1)\ (K+2)}{3}\left\{\frac{dn}{n}+\frac{dA'}{A'}\right\} \qquad \ldots \quad (2)$$

While there is no doubt that the above relation will be perfectly valid if the medium as a whole undergoes the change denoted by dn and dA', the validity is questionable if the particular changes are confined to a very small volume element. To see this clearly, it is necessary to recollect how the factor (K+2)/ 3 arises. The total field acting on a molecule within a liquid is obtained as follows. Consider a long cylindrical cavity described round the molecule, the axis of the cylinder being along the direction of the external field. The length of the cylinder should be very great compared with its radius and the radius, though small in the physical sense, should be many times the diameter of a molecule. The intensity at the molecule will now be Z, that of the external field. If the cavity is now filled with the molecules that have been removed, an additional intensity will be caused. The filling can be done in two steps, (1) up to the boundary of a sphere surrounding the molecule, the cylinder being tangential to the sphere and (2) within the sphere. The first of these will cause a field $\frac{4}{3}\pi nM$ at P, where M is the mean induced moment of the molecules outside the sphere. The molecules within the sphere will cause no

effect at the centre provided they are arranged in cubical order with the central molecule at one of the cube corners or, on the average, when the surrounding molecules can take up continuously-varying positions and orientations as in a liquid. The resultant field will therefore be $Z+\frac{4}{3}\pi n M$ or $Z(K+2)/3$, where K is the dielectric constant of the matter outside the imaginary sphere.

If there is any local deviation of n or M in the region surrounding the molecule, it would cause an additional field whose sign may be positive or negative according to the sign of the deviation and its position with respect to the molecule. Even though the deviation is positive, it would cause a negative field if, for example, it is located in a direction at right angles to the field. When there are many such local deviations of n or M distributed at random round the molecule, the extra addition to the local field need not necessarily be proportioned to the change of nM in a small volume element round the molecule.

In obtaining the intensity of scattering from a finite volume of the liquid, we divide it into *small* volume elements and consider the waves scattered from the parts of each volume element to be coherent. The only restrictions on the size of these volume elements are that their linear dimensions should be small compared with the wave-length and that they should be sufficiently large for the fluctuations of density in one to be independent of those in another. There must be a minimum limit to the size of the volume element of a liquid under definite conditions of pressure and temperature so that the latter condition may be satisfied. This limiting volume is not easy to determine, but some idea about its magnitude can be obtained from the following considerations. Liquid benzene, for example, at 30°C. has a compressibility of 103×10^{-6} per atmosphere, which is about 1/35 of that of a perfect gas of the same molecular concentration. Since the mean square of the deviations of density

in a volume element is proportional to the compressibility and since the fluctuations in a perfect gas are determined by the circumstance that the position of one molecule is uncorrelated with the positions of other molecules, we may take it that the fluctuations of density in a volume element in *liquid benzene* at 30°C. are uncorrelated with those in other volume elements if it contains on the average not less than 35 molecules. If the volume elements are so small as to contain fewer molecules than this and one of them has at a certain instant more than the average density of molecules, then other volume elements in the immediate neighbourhood will have fewer molecules, that is, the correlation between the deviations of density in neighbouring volume elements would be negative. To take another example, liquid CO_2 at 30°C. in equilibrium with its vapour has a compressibility nearly 20 times that of a perfect gas of the same molecular concentration. Here as before, the minimum size of the volume element required to justify the assumption of independence of density-fluctuations will be that it should contain not fewer than 20 molecules, but in neighbouring volume elements of smaller size than this, the fluctuations of concentration will be positively correlated. Except in the immediate neighbourhood of the critical point, we may safely take that the fluctuations of density in different volume elements are independent if they contain not less than 50 molecules.

Now, the amplitude of the scattered waves from each volume element will be proportional to the number of molecules contained in it without any regard to how they are distributed inside, and to the average field at the molecules. The value of the latter depends on the dielectric constant outside the imaginary sphere described round it. Even if we take the sphere so small that its radius is only three times the average distance between two molecules, it will contain more than 110 molecules and hence the fluctuations of density inside the sphere will have very little correlation with those

outside. The volume of polarised matter responsible for the extra local field at the molecules of a volume element is thus not only larger than the volume element itself, but the fluctuations of density in it are independent of those in the element. Hence, the fluctuations of local field at the molecules of a volume element will be uncorrelated with those of density in the element. Thus, in equation (1), which may also be written in the form

$$\mathrm{K}-1=\left(\frac{\mathrm{K}+2}{3}\right)4\pi n\mathrm{A}',$$

the K's on the two sides of the equation are not identical; while the K on the left hand side changes with the fluctuations of density in the volume element, the K on the right hand side does not. If the latter be treated as constant,

$$d\mathrm{K}=(\mathrm{K}-1)\left\{\frac{dn}{n}+\frac{d\mathrm{A}'}{\mathrm{A}'}\right\} \qquad \ldots \quad (3)$$

It has been tacitly assumed in the above that the fluctuations of local field caused by the variations of molecular polarisability are altogether negligible. When a liquid is not subjected to electric or magnetic fields, the latter arise mainly from the varying orientations of anisotropic molecules. If we assume that the orientations of different molecules are uncorrelated with each other, the mean deviation of polarisability in a small volume element will also be uncorrelated with the average local field at the molecules since it depends mainly on the polarisation of the surrounding medium beyond the bounds of the volume element.

3. *Molecular theory of scattering.*

We may thus consider equation (3) as more correctly representing the relation between the deviations in dielectric constant, molecular concentration and molecular polarisability than equation (2). It was shown in paper A that in

a medium composed of isotropic molecules, the electric intensity at a distant point P due to scattering from δv is

$$\frac{p^2}{c^2 d} \sin\theta' \, \delta v . \, \mathrm{M}n$$

where $p/2\pi$ is the frequency of the incident radiation, c is the velocity of light in vacuo, θ' the angle between the scattered wave and the direction of the electric vector in the incident radiation, M the moment induced in a molecule and n the density of molecules contained in the volume element. Subtracting the part common to all volume elements which would destroy each other by interference, the excess electric intensity in the scattered wave will be

$$\frac{p^2}{c^2 d} \sin\theta'(\mathrm{M}n - \mathrm{M}_0 n_0)\delta v$$

where M_0 and n_0 are the mean values of the moment and density respectively.

It was assumed in paper A that M is the moment appropriate to density n, but since as we have seen, its value is not appreciably affected by the fluctuations of density, M can be equated to M_0 and the above expression will reduce to

$$\frac{p^2}{c^2 d} \sin\theta' \mathrm{M}_0 \delta n . \delta v \qquad \ldots \quad (4)$$

and the square of the electric intensity at P due to scattering from δv will be

$$\frac{p^4}{c^4 d^2} \sin^2\theta' \, \frac{(\mathrm{K}_0 - 1)^2}{16\pi^2} \, \mathrm{Z}^2 \, \frac{\delta n^2}{n_0^2} \, . \, \delta v^2$$

The mean value of this quantity is

$$\overline{\mathrm{E}^2} = \frac{p^4 \sin^2\theta'}{c^4 d^2} \, \frac{(\mathrm{K}_0 - 1)^2}{16\pi^2} \, \mathrm{Z}^2 \, \frac{\overline{\delta n^2}}{n_0^2} \delta v^2$$

$$= \frac{\pi^2 \mathrm{RT}\beta}{\mathrm{N}\lambda^4} \, (\mathrm{K}_0 - 1)^2 \, \frac{\sin^2\theta'}{d^2} . \, \delta v \qquad \ldots \quad (5)$$

When the incident light is unpolarised, the intensity of the transversely scattered light from a finite volume V is

$$I=\frac{I_0 V}{d^2}\ \frac{\pi^2 RT\beta}{2N\lambda^4}(K_0-1)^2 \qquad \ldots \quad (6)$$

where I_0 is the intensity of the incident light. This differs from the expression given in paper A by the suppression of the factor $(K_0+2)^2/9$.[1]

Turning now to the case of a liquid composed of anisotropic molecules, the Z component of the electric intensity in the light scattered from δv at P is, as shown in page 184 of paper B

$$\frac{p^2}{c^2 d} Z\left(\frac{K+2}{3}\right) L_3 n\delta v \qquad \ldots \quad (7)$$

where

$$L_3=C\cos^2\theta+B\sin^2\theta\sin^2\phi+A\sin^2\theta\cos^2\phi$$

A, B and C being the polarisabilities of each molecule along three principal directions and θ, ϕ, ψ being the Eulerian angles defining the directions of the molecular axes with respect to the co-ordinate axes. The above can be written

$$\frac{p^2}{c^2 d} Z\left(\frac{K+2}{3}\right)\left\{\frac{A+B+C}{3}+\left(L_3-\frac{A+B+C}{3}\right)\right\} n\delta v \qquad \ldots \quad (7a)$$

$$=\frac{p^2}{c^2 d} Z\left(\frac{K+2}{3}\right)\left\{\frac{A+B+C}{3} n_0\delta v+\frac{A+B+C}{3}\delta n\delta v\right.$$

$$\left.+\left(L_3-\frac{A+B+C}{3} ndv\right)\right\} \qquad \ldots \quad 7(b)$$

in which $n_0+\delta n$ is substituted for n.

[1] M. Born in his paper on Scattering in Phys. Zeit. Nr. 1/4 p. 16 (1918) and L. V. King in his letter to Nature (cxi, p. 667, 1923) have both omitted this factor, but without giving reasons.

Of the three terms in the last expression, the first is constant for every equal volume element and the third varies from molecule to molecule. When finite volume elements are considered, the first term cancels by interference, the second is summed by adding together the squares of the electric vector from the different volume elements and the third by adding together the squares of the electric vector from the different molecules. The last term is the one introduced owing to the anisotropy of the molecules. If the K in (K+2)/3 is taken to be the mean dielectric constant of the liquid, it can easily be shown that the total value of Z'^2 from a volume V is

$$\overline{Z'^2} = \frac{p^4}{c^4 d^2} Z^2 \left(\frac{K_0+2}{3}\right)^2 n_0 V \left\{\left(\frac{A+B+C}{3}\right)^2 \frac{RT\beta n_0}{N} + \frac{4}{3} f\right\}$$

where

$$f = \tfrac{1}{15}(A^2+B^2+C^2-AB-BC-CA)$$

As was shown in paper B (equation 1)

$$\overline{X'^2} = \frac{p^4}{c^4 d^2} Z^2 \left(\frac{K_0+2}{3}\right)^2 f n_0 V$$

Hence

$$\frac{\overline{X'^2}}{\overline{Z'^2}} = \frac{f}{\left(\frac{A+B+C}{3}\right)^2 \frac{RT\beta n_0}{N} + \frac{4}{3} f}$$

If the incident light is unpolarised, the ratio of the weak component to the strong in the transversely scattered light is

$$r = \frac{2f}{\left(\frac{A+B+C}{3}\right)^2 \frac{RT\beta n_0}{N} + \frac{4}{3}}$$

$$= \frac{6\delta}{\frac{5RT\beta n_0}{N} + 7\delta} \qquad \ldots (8)$$

where

$$\delta = (A^2+B^2+C^2-AB-BC-CA)/(A+B+C^2)$$

And the intensity of the light scattered in the transverse direction expressed in terms of r is

$$\frac{I_0 V}{d^2} \frac{RT\beta}{2N\lambda^4}(K_0-1)^2 \frac{6(1+r)}{6-7r} \quad \ldots (9)$$

The value of the co-efficient of attenuation can easily be shown to be

$$h = \frac{8\pi^3}{3} \frac{RT\beta}{N\lambda^4}(K_0-1)^2 + \frac{8\pi^3}{3n_0\lambda^4}(K_0-1)^2 2\delta$$

$$= \frac{8\pi^3}{3n_0\lambda^4}(K_0-1)^2 \left\{ \frac{RT\beta n_0}{N} + 2\delta \right\} \quad \ldots (10)$$

4. Gans's theory of scattering.

Lord Rayleigh's expression for the scattering of light by a particle whose linear dimensions are small in comparison with the wave-length, when its dielectric constant differs by only a small amount from that of the surrounding medium, takes the form[1]

$$\frac{I}{I_0} = \frac{\pi^2 \wedge^2}{2\lambda^4 d^2} (\delta v)^2 \ (1+\cos^2\chi) \quad \ldots (11)$$

where $\wedge$ is the deviation in dielectric constant of the particle, χ is the angle between the incident and scattered beams, and δv is the volume of the particle. When we substitute for $\wedge^2$ the mean value of the square of the fluctuations of dielectric constant taking place in a volume element δv of a pure liquid and assume that these are solely caused by the fluctuations of density, we have

$$\overline{\wedge^2} = \left(\frac{\delta K}{\delta \rho}\right) \ \overline{\delta\rho^2}$$

$$= \left(\frac{\delta K}{\delta \rho}\right)^2 \frac{RT\beta}{N\delta v} \rho^2$$

[1] Lord Rayleigh. Scientific papers, Vol. i, p. 526.

and equation (11) becomes

$$\frac{I}{I_0} = \frac{\pi^2 RT\beta}{2N\lambda^4 d^2} \rho^2 \left(\frac{\delta K}{\delta \rho}\right)^2 \delta v \,(1 + \cos^2\chi) \qquad \ldots \quad (12)$$

which can easily be seen to be identical with Einstein's expression.

If now we consider the deviations of dielectric constant of a volume element δv to be anisotropic, the intensity of scattering will be increased and the transversely scattered light will also appear partially polarised. Let $\wedge_1$, $\wedge_2$, $\wedge_3$ be the deviations of optical dielectric constant of a volume element δv along three principal directions of anisotropy and let $\wedge_1 = \wedge + \lambda_1$, $\wedge_2 = \wedge + \lambda_2$, $\wedge_3 = \wedge + \lambda_3$, $\bar{\lambda}_1 + \bar{\lambda}_2 + \bar{\lambda}_3$ being equal to zero. Then $\wedge$ is the purely isotropic part of the deviations and λ_1, λ_2, λ_3 the purely anisotropic part. $\overline{\wedge^2}$ is identified with the $(\delta K/\delta\rho)^2 \delta\rho^2$ of Einstein's theory. Gans showed that the imperfection of polarisation of the scattered light in a direction at right angles to the incident unpolarised beam, which is measured by the ratio of the intensity of the weak component that of the strong is given by

$$r = \frac{\overline{(\wedge_1^2 + \wedge_2^2 + \wedge_3^2)} - 2\,\overline{(\wedge_1\wedge_2 + \wedge_2\wedge_3 + \wedge_3\wedge_1)}}{4\overline{(\wedge_1^2 + \wedge_2^2 + \wedge_3^2)} + \overline{(\wedge_1\wedge_2 + \wedge_2\wedge_3 + \wedge_3\wedge_1)}} \qquad (13)$$

and the intensity in the same direction from a volume δv by

$$\frac{I}{I_0} = \frac{\pi^2 \overline{\wedge^2}}{2\lambda^4 d^2} (\delta v)^2 \frac{6+6r}{6-7r} \qquad \ldots \quad (14)$$

This differs from the expression on the right-hand side of (11) (with $\chi = \pi/2$) by the introduction of the factor

$6(1+r)/(6-7r)$. The co-efficient of attenuation was obtained by Gans to be

$$h = \frac{8\pi^3}{3\lambda^4} \quad \frac{\overline{\wedge_1^2} + \overline{\wedge_2^2} + \overline{\wedge_3^2}}{3} \delta v$$

$$= \frac{8\pi^3}{3\lambda^4}\left(\overline{\wedge^2} + \frac{\overline{\lambda_1^2} + \overline{\lambda_2^2} + \lambda_3^2}{3} \right) \delta v \qquad \ldots \quad (15)$$

Gans next connects the anisotropic part of the fluctuations of dielectric constant with the Kerr constant of electric double refraction somewhat on the same lines as in Langevin's work connecting molecular anisotropy with electric double refraction. It may be useful to give a summary of Gans's treatment. If anisotropic fluctuations of dielectric constant occur in a liquid, there will also be similar fluctuations of electrostatic dielectric constant. In an isotropic liquid, the fluctuations will be in random directions, but when an electrostatic field is put on, the directions will no longer be random, but there will be a tendency for the largest of the three principal dielectric constants to set themselves along the direction of the field, so that when a beam of light is passed through the medium perpendicular to the field, the velocities of the components parallel and perpendicular to it will be unequal, that is, the medium will become doubly refracting. If $\wedge_1^\circ$, $\wedge_2^\circ$, $\wedge_3^\circ$ be the three principal deviations of electrostatic dielectric constant of a volume element and they make angles whose cosines are γ_1, γ_2 and γ_3 with the applied electrostatic field E_0 (parallel to OZ), then the difference of potential energy of the volume element from that of an isotropic volume element containing the same mass but having the mean dielectric constant of the liquid is

$$-\frac{E_0^2}{8\pi} \delta v(\wedge_1^\circ \gamma_1^2 + \wedge_2^\circ \gamma_2^2 + \wedge_3^\circ \gamma_3^2) \qquad \ldots \quad (16)$$

By Boltzmann's theorem, the probability that one of the principal axes of a volume element has its direction between

θ and $\theta+d\theta$, ϕ and $\phi+d\phi$, and ψ and $\psi+d\psi$, where θ is the angle between the direction of the field and the axis under consideration and ϕ and ψ have their usual significance, is

$$e^{Q(\Lambda_1^0\gamma_1^2+\Lambda_2^0\gamma_2^2+\Lambda_3^0\gamma_3^2)} \sin\theta\, d\theta\, d\phi\, d\psi$$

where

$$Q=E_0^2 N\,\delta v/8\pi RT$$

By the usual method of obtaining mean values

$$\overline{\gamma_1^2}=\frac{\iiint \gamma_1^2 e^{Q(\Lambda_1^0\gamma_1^2+\Lambda_2^0\gamma_2^2+\Lambda_3\gamma_3^2)} \sin\theta\, d\theta\, d\phi\, d\psi}{\iiint e^{Q(\Lambda_1^0\gamma_1^2+\Lambda_2^0\gamma_2^2+\Lambda_3^0\gamma_3^2)} \sin\theta\, d\theta\, d\phi\, d\psi}$$

Reducing, we get

$$\overline{\gamma_1^2}=\frac{1}{3}+\frac{2Q}{15}\left(\Lambda_1^0-\frac{\Lambda_1^0+\Lambda_2^0+\Lambda_3^0}{3}\right)$$

$$\overline{\gamma_2^2}=\frac{1}{3}+\frac{2Q}{15}\left(\Lambda_2^0-\frac{\Lambda_1^0+\Lambda_2^0+\Lambda_3^0}{3}\right)$$

and

$$\overline{\gamma_3^2}=\frac{1}{3}+\frac{2Q}{15}\left(\Lambda_3^0-\frac{\Lambda_1^0+\Lambda_2^0+\Lambda_3^0}{3}\right) \quad \ldots (17)$$

Gans takes the change of dielectric constant of the medium as a whole in the direction of the Z-axis to be the average change of dielectric constant of the volume elements composing it, in that direction. Thus

$$K_z-K_0=(\overline{\Lambda_1\gamma_1^2}+\overline{\Lambda_2\gamma_2^2}+\overline{\Lambda_3\gamma_3^2}) \quad \ldots (18)$$

Substituting the value for $\overline{\gamma_1^2}$, $\overline{\gamma_2^2}$, $\overline{\gamma_3^2}$ and remembering that $\overline{\Lambda_1}+\overline{\Lambda_2}+\overline{\Lambda_3}=0$,

$$K_z-K_0=\frac{2Q}{15}\left\{\overline{(\Lambda_1^0\Lambda_1+\Lambda_2^0\Lambda_2+\Lambda_3^0\Lambda_3)}-\frac{\overline{(\Lambda_1^0+\Lambda_2^0+\Lambda_3^0)}\ \overline{(\Lambda_1+\Lambda_2+\Lambda_3)}}{3}\right\} \quad (19)$$

Similarly, evaluating $\overline{a_1^2}$, $\overline{a_2^2}$ $\overline{a_3^2}$ where α_1, α_2, α_3 are the angles made by the directions of Λ_1^0, Λ_2^0, Λ_3^0 with OX he gets

$$\overline{a_1^2} = \frac{1}{3} - \frac{Q}{15}\left(\Lambda_1^0 - \frac{\Lambda_1^0 + \Lambda_2^0 + \Lambda_3^0}{3} \right)$$

with similar expressions for $\overline{a_2^2}$ and $\overline{a_3^2}$.

$$K_z - K_0 = \overline{\Lambda_1 a_1^0 + \Lambda_2 a_2^2 + \Lambda_3 a_3^2}$$

$$= -\frac{Q}{15}\left(\overline{\Lambda_1^0 \Lambda_1} + \overline{\Lambda_2^0 \Lambda_2} + \overline{\Lambda_3^0 \Lambda_3} \right.$$

$$\left. - \frac{\overline{(\Lambda_1^0 + \Lambda_2^0 + \Lambda_3^0)(\Lambda_1 + \Lambda_2 + \Lambda_3)}}{3} \right) \quad \ldots \quad (20)$$

If we write ν_z and ν_x for the refractive indices for vibrations parallel and perpendicular to the field (ν_z^2 being equal to K_z) etc., and ν for the mean refractive index,

$$\frac{\nu_z - \nu_x}{E_0^2} = \frac{N\delta v}{80\pi\nu RT} \left\{ \overline{\Lambda_1^0 \Lambda_1} + \overline{\Lambda_2^0 \Lambda_2} + \overline{\Lambda_3^0 \Lambda_3} \right.$$

$$\left. - \frac{\overline{(\Lambda_1^0 + \Lambda_2^0 + \Lambda_3^0)(\Lambda_1 + \Lambda_2 + \Lambda_3)}}{3} \right\} \quad \ldots \quad (21)$$

Assuming that

$$\frac{\Lambda_1^0}{\Lambda_1} = \frac{\Lambda_2^0}{\Lambda_2} = \frac{\Lambda_3^0}{\Lambda_3} = \frac{(\epsilon - 1)(\epsilon + 2)}{(\nu^2 - 1)(\nu^2 + 2)} \quad \ldots \quad (22)$$

where ϵ is the electrostatic dielectric constant, equation (21) becomes

$$\frac{\nu_z - \nu_x}{E_0^2} = \frac{N\delta v}{80\pi\nu RT} \frac{(\epsilon - 1)(\epsilon + 2)}{(\nu^2 - 1)(\nu^2 + 2)} \left\{ \overline{\Lambda_1^2} + \overline{\Lambda_2^2} + \overline{\Lambda_3^2} - \frac{\overline{(\Lambda_1 + \Lambda_2 + \Lambda_3)^2}}{3} \right\}$$

$$= \frac{N\delta v}{80\pi\nu RT} \frac{(\epsilon - 1)(\epsilon + 2)}{(\nu^2 - 1)(\nu^2 + 2)} \left(\overline{\lambda_1^2} + \overline{\lambda_2^2} + \overline{\lambda_3^2} \right)$$

Since the Kerr constant

$$B^1=(\nu_z-\nu_x)/\lambda E_0^2$$

$$\overline{\lambda_1^2}+\overline{\lambda_2^2}+\overline{\lambda_3^2}=\frac{80\pi\nu RT\lambda B^1(\nu^2-1)(\nu^2+2)}{N\delta v(\epsilon-1)(\epsilon+2)} \quad \ldots \quad (23)$$

Substituting this value in (15) and writing

$$\overline{\wedge^2}=\frac{(\nu^2-1)^2(\nu^2+2)^2}{9}\quad\frac{RT\beta}{N\delta v}$$

Gans obtains the co-efficient of attenuation to be

$$h=\frac{8\pi^3}{3}\frac{RT}{N\lambda^4}\left\{\frac{\beta(\nu^2-1)^2(\nu^2+2)^2}{9}+\frac{80\pi v\lambda B^1}{3}\frac{(\nu^2-1)(\nu^2+2)}{(\epsilon-1)(\epsilon+2)}\right\}\ldots \quad (24)$$

5. *Discussion of Gans's theory.*

The quantity

$$\overline{\lambda_1^2}+\overline{\lambda_2^2}+\overline{\lambda_3^2}$$

which is determined in (23) differs, however, in an important way from the same expression in (15). Gans's assumption in (22) that

$$\wedge_1^0/\wedge_1 \text{ etc.}=\frac{(\epsilon-1)(\epsilon+2)}{(\nu^2-1)(\nu^2+2)}$$

is equivalent to assuming

$$\lambda_1^0/\lambda_1, \text{ etc.}=(\epsilon-1)(\epsilon+2)/(\nu^2-1)(\nu^2+2),$$

as can easily be seen by reducing (21) in terms of $\wedge^0$, $\wedge$ and λ_1^0, λ_1, etc. In a liquid under ordinary conditions, the anisotropic fluctuations of dielectric constant of different volume elements (even when they are very small and contain only a few molecules) are entirely uncorrelated with each other, but when the liquid is placed in an electrostatic field, the axis of largest dielectric constant in each volume element tends to place itself parallel to the field. The resulting change in

dielectric constant is conditioned not only by the turning of the anisotropic volume elements, but also by the change in local field produced by such *general* turning. The potential energy of an anisotropic volume element when the medium is placed in an electrostatic field E_0 is written by Gans to be

$$-\frac{E_0^2}{8\pi}\left(\Lambda_1{}^0\gamma_1^2+\Lambda_2{}^0\gamma_2^2+\Lambda_3{}^0\gamma_3^2\right)\delta v, \qquad \ldots \quad (25)$$

This may also be written

$$\frac{-E_0^2\delta v}{8\pi}\left\{\Lambda^0+(\lambda_1{}^0\gamma_1^2+\lambda_2{}^0\gamma_2^2+\lambda_3{}^0\gamma_3^2)\right\} \qquad \ldots \quad (26)$$

Now, $\lambda_1{}^0\gamma_1^2+\lambda_2{}^0\gamma_2^2+\lambda_3{}^0\gamma_3^2$ is the anisotropic deviation in dielectric constant in the direction of the field if the change due to the field is confined to the particular volume element so that the local polarisation field is not affected. But since a correlated change of dielectric constant is suffered by every volume element, the actual anisotropic deviation in dielectric constant will be

$$\left(\frac{\epsilon+2}{3}\right)(\lambda_1{}^0\gamma_1^2+\lambda_2{}^0\gamma_2+\lambda_3{}^0\gamma_3^2)$$

[compare equations (2) and (3)] and the second term in expression (26) for the potential energy will become

$$-\frac{E_0^2\delta v}{8\pi}\left\{\frac{\epsilon+2}{3}\right\}(\lambda_1{}^0\gamma_1^2+\lambda_2{}^0\gamma_2^2+\lambda_3{}^0\gamma_3^2) \qquad \ldots \quad (27)$$

This term alone is of importance in determining electric double refraction. $\overline{\gamma_1^2}$ will therefore become equal to

$$\frac{1}{3}+\frac{2Q}{15}\left(\frac{\epsilon+2}{3}\right)\left(\lambda_1{}^0-\frac{\lambda_1{}^0+\lambda_2{}^0+\lambda_3{}^0}{3}\right)$$

and $\overline{\gamma_2^2}$ and $\overline{\gamma_3^2}$ will also get similarly altered.

Expression (18) will also get changed to

$$K_z - K_0 = \left(\frac{\nu^2+2}{3}\right)\left(\overline{\lambda_1\gamma_1^2} + \overline{\lambda_2\gamma_2^2} + \overline{\lambda_3\gamma_3^2}\right)$$

$\overline{\Lambda_1} + \overline{\Lambda_2} + \overline{\Lambda_3}$ being equal to zero.

Therefore,

$$\frac{K_z - K_x}{E_0^2} = \frac{N\delta v}{40\pi RT}\left(\frac{\epsilon+2}{3}\right)\left(\frac{\nu^2+2}{3}\right)\frac{\lambda_1^0}{\lambda_1}\cdot\left\{\overline{\lambda_1^2} + \overline{\lambda_2^2} + \overline{\lambda_3^2} - \frac{\overline{(\lambda_1+\lambda_2+\lambda_3)^2}}{3}\right\} \quad \ldots (28)$$

If the average field acting on the molecules of a small volume element in the absence of an electrostatic field is unaffected by the anisotropic fluctuations of dielectric constant and if we assume that the directions of the principal electrostatic and optical polarisabilities in each molecule are the same and their magnitudes are proportional to each other,

$$\frac{\lambda_1^0}{\lambda_1} = \frac{\epsilon-1}{\nu^2-1}$$

and

$$\frac{\nu_x - \nu_z}{E_0^2} = \frac{N\delta v}{80\pi\nu RT}\cdot\frac{\epsilon-1}{\nu^2-1}\cdot\frac{\epsilon+2}{3}\cdot\frac{\nu^2+2}{3}\cdot\left(\overline{\lambda_1^2} + \overline{\lambda_2^2} + \overline{\lambda_3^2}\right)$$

$$= \frac{N\delta v}{80\pi\nu RT}\cdot\frac{(\epsilon-1)(\epsilon+2)}{(\nu^2-1)(\nu^2+2)}\left(\frac{\nu^2+2}{3}\right)^2\left(\overline{\lambda_1^2} + \overline{\lambda_2^2} + \overline{\lambda_3^2}\right)$$

$$\therefore \left(\overline{\lambda_1^2} + \overline{\lambda_2^2} + \overline{\lambda_3^2}\right) = \frac{80\pi\nu RT}{N\delta v}\cdot\frac{\lambda B^1.}{(\epsilon-1)(\epsilon+2)}\cdot\frac{(\nu^2-1)(\nu^2+2)}{(\nu^2+2)^2}\cdot\frac{9}{} \quad (29)$$

If at the same time for reasons discussed in section I, we take

$$\overline{\Lambda_1^2} = \frac{(\nu^2-1)^2 RT\beta}{N\delta v},$$

Gans's expression (24) for h will get transformed into

$$h = \frac{8\pi^3}{3} \frac{RT}{N\lambda^4} \left\{ \beta(\nu^2-1)^2 \frac{80\pi\nu\lambda B^1}{(\nu^2+2)} \cdot \frac{(\nu_2-1).3}{(\epsilon-1)(\epsilon+2)} \right\} \quad \ldots \quad (30)$$

6. *Anisotropic fluctuations of dielectric constant in terms of molecular constants.*

It can easily be seen that anisotropic fluctuations of dielectric constants of small volume elements are a necessary consequence of the anisotropy of the individual molecules. Consider a small volume element of an isotropic liquid composed of anisotropic molecules. Since the molecular axes are by hypothesis oriented at random, the number of molecules pointing in directions included within any small solid angle will not, in general, be exactly the same as the number pointing in directions included within another equal solid angle pointing in some other direction. Thence will arise a residual anisotropy of the volume element whose magnitude and direction will vary from instant to instant. The smaller the number of molecules, the greater will be the fluctuations from isotropy.

We have already seen that in a small volume element of of an isotropic liquid under normal conditions

$$\delta K = (K_0-1)\left(\frac{\delta n}{n} + \frac{\delta A'}{A'} \right)$$

$$\therefore \quad \overline{\delta K^2} = (K_0-1)^2 \left\{ \frac{\overline{\delta n^2}}{n^2} + \frac{\overline{\delta A'^2}}{A'^2} \right\} \quad \ldots \quad (31)$$

where it is assumed that δn and $\delta A'$ are independent of each other. The first term of the above equation can be identified with $\overline{\Lambda^2}$ and the second with

$$(\overline{\lambda_1^2} + \overline{\lambda_2^2} + \overline{\lambda_3^2})/3.$$

It suffices now to evaluate

$$\overline{\delta A'^2}/A'^2.$$

When a unit field parallel to the axis of Z is applied to the medium, the mean value of the square of the sum of the induced moments of the molecules is [See 7(a) and 7(b) above]

$$\overline{\left\{\frac{A+B+C}{3}\right\}^2 n^2\delta v^2} + \overline{\sum\left\{L_s - \frac{A+B+C}{3}\right\}^2}$$

$$= \left(\frac{A+B+C}{3}\right)^2 n_0^2\delta v^2 + \overline{\left(\frac{A+B+C}{3}\right)^2 \delta n^2\delta v^2} + n_0\delta v.\ \tfrac{4}{3}f$$

Of these, only the last term contributes to $\delta A'^2$. The mean value of the squares of the moments induced parallel to the X and Y axis will each be

$$n_0\delta v.\ f. \qquad \text{(Paper B, Eq, 1)}$$

$$\therefore\quad \overline{\delta A'^2} = \frac{n_0\delta v.(\frac{4}{3}f+2f)}{n_0^2\delta v^2} = \frac{10}{3}f\Big/n_0\delta v. \qquad \ldots\ (32)$$

and

$$\frac{\overline{\lambda_1^2}+\overline{\lambda_2^2}+\overline{\lambda_3^2}}{3} = (K_0-1)^2\ \frac{\frac{10}{3}\cdot\frac{1}{15}(A^2+B^2+C^2-AB-BC-CA)}{\left(\frac{A+B+C}{3}\right)^2 n_0\delta v}$$

$$= \frac{2(K_0-1)^2(A^2+B^2+C^2-AB-BC-CA)}{(A+B+C)^2 n_0\delta v}$$

$$= \frac{2(K_0-1)^2\delta}{n_0\delta v} = \frac{2(\nu^2-1)^2\delta}{n_0\delta v} \qquad \ldots\ (33)$$

Identifying this $\overline{\lambda_1^2}+\overline{\lambda_2^2}+\overline{\lambda_3^2}$ derived from *a priori* considerations with the same quantity expressed in terms of the Kerr constant in (29), we can express B^1 in terms of δ

$$B' = \frac{(\nu^2-1)(\nu^2+2)(\epsilon-1)(\epsilon+2)N\delta}{120\pi RTn_0\nu\lambda} \quad \ldots (34)$$

on the assumption that the principal axes of dielectric and optical constants are parallel and proportional to each other. This is the same expression as is obtained on Langevin's theory of electrical double refraction.[1]

In terms of molecular constants,

$$h = \frac{8\pi}{3\lambda^4}\left\{\overline{\Lambda^2} + \frac{\overline{\lambda_1^2}+\overline{\lambda_2^2}+\overline{\lambda_3^2}}{3}\right\}\delta v$$

$$= \frac{8\pi}{3n_0\lambda^4}\left\{\frac{RT\beta n_0}{N}+2\delta\right\}(K_0-1)^2 \quad \ldots (35)$$

which is identical with (10).

The expression for the intensity in a transverse direction also becomes the same as (9).

7. *Comparison of phenomenological and molecular theories.*

We see from the above that both the phenomenological and molecular theories lead exactly to the same result, and this is what is to be expected. Strictly, the phenomenological theory itself is partly molecular, since in developing it, we have to use the Lorentz formula of refraction which is based on molecular considerations. As regards the theory of

[1] P. Debye, Handbuch der Radiologie, Band VI, p. 768. Also K. S. Krishnan, Proc. Ind. Assoc. Cult. of Science, Vol. IX, Part IV, p. 251.

electric double refraction, the advantage lies with the molecular way of treatment. It is more direct and simple and is capable of extension to the case when the molecules possess a permanent electric moment.[1] And since we know for a certainty from the partial polarisation of the transversely scattered light in gases and vapours that molecules are in general optically anisotropic, there is nothing to be gained by avoiding that assumption and preferring instead the assumption of anisotropic dielectric constants of small elements of volume.

In a recent paper, Mr. K. S. Krishnan[2] has compared the available experimental data on light-scattering in liquids with different formulæ that have been proposed from time to time and shown that so far as comparative values of intensities are concerned, relation (9) is in better agreement with experiment than the formulæ involving $(K+2)^2/9$ as a factor. As regards absolute measurements, the data are not decisive, but it is hoped that results of critical measurements of intensity in a few selected liquids will soon be available to decide the question. Measurements near the critical temperature are not of much help in this respect, as the values of $(K+2)^2/9$ in that region generally differ very little from unity.

Mr. Krishnan has utilized the data about polarisation to calculate the values of δ which gives a measure of the optical anisotropy of the molecule and compared them with the values calculated from the Kerr constant of electric double refraction according to (34). Here again, he finds that values of δ given by the revised expressions are in better agreement with the values calculated from the Kerr constant. It may be mentioned that liquids containing polar molecules are excluded from consideration.

[1] C. V. Raman and K. S. Krishnan, Nature, Vol. 118, p. 302, 1926; also same authors Phil. Mag., Vol. 3, pp. 713-723 and pp. 724-735, April 1927.

[2] K. S. Krishnan, *loc. cit.*

8. *Binary Liquid Mixtures.*

The arguments discussed in Sections 1 and 2 should also be applicable to the fluctuations of concentration in a binary liquid mixture. In a detailed paper[1] on the "Opalescence of binary liquid mixtures," Dr. J. C. K. Rav has obtained the following expression for the intensity of the transversely scattered light from a volume V

$$\frac{p^4 Z^2}{c^4 d^2} V \left\{ \frac{13}{3} \cdot \left(\frac{K+2}{3} \right)^2 (f_1 n_1 + f_2 n_2) + \frac{(K-1)^2 (K+2)^2}{144\pi^2} \cdot \frac{RT\beta}{N} \right.$$

$$\left. + \frac{1}{16\pi^2} \cdot \frac{M_2}{N m_1} \frac{(\partial K/\partial k)^2}{\partial \log p_2/\partial k} \right\} \quad \ldots \quad (36)$$

(See equation 41 on p. 45) where f_1, f_2 are the values of f which is equal to

$$\tfrac{1}{15}(A^2 + B^2 + C^2 - AB - BC - CA)$$

for the first and second components respectively, n_1, n_2 are the numbers of molecules of the two components per unit of volume, M_2 is the molecular weight in the gaseous phase and p_2 the partial vapour pressure, of the second component, m_1 and m_2 are the masses of the first and second components in unit volume of the mixture and k is the fraction m_2/m_1. The factor $(K+2)^2/9$ in the second term is introduced in the same manner as in the previous treatments of liquids with isotropic

[1] J. C. K. Rav. Proc. Ind. Assoc. for Cult. of Science, Vol. IX, Part I, p. 19 (1924).

molecules, that is, assuming that the local field in a small volume element changes with the changes of density in the element. According to section 2, this factor should be omitted.

$\partial K/\partial k$ in the third term is obtained by measuring the tangent at desired points from a graph showing the variation of K with k. These values are appropriate to the case where similar changes of concentration occur throughout the liquid. When the deviations of concentration from normal in different volume elements are uncorrelated with each other, the changes of dielectric constant in them will be due solely to these changes of concentration and the local field will remain unaffected. The values of $\partial K/\partial k$ which we should adopt are therefore not those obtaining when similar changes of concentration occur throughout the liquid, but these values divided by a factor $(K+2)/3$. Making these changes, expression (36) will become

$$\frac{p^4 Z^2}{c^4 d^2} V \left\{ \frac{13}{3} \frac{(K+2)^2}{9} (f_1 n_1 + f_2 n_2) + \frac{(K-1)^2}{16\pi^2} \frac{RT\beta}{N} + \frac{1}{16\pi^2} \frac{M_2 (\partial K/\partial k)^2}{N m_1 \partial \log p_2/\partial k} \cdot \frac{9}{(K+2)^2} \right\} \quad \ldots (37)$$

and equation (40) of Dr. Rav's paper for the depolarisation of the transversely scattered light will be changed to

$$\frac{\frac{2(K+2)^2}{9} (f_1 n_1 + f_2 n_2)}{\frac{7}{3}\left(\frac{K+2}{3}\right)^2 (f_1 n_1 + f_2 n_2) + \frac{(K-1)^2}{16\pi^2} \frac{RT\beta}{N} + \frac{9}{16\pi^2 (K+2)^2} \frac{M_2 (\partial K/\partial k)^2}{N m_1 \partial \log p_2/\partial k}}$$

The available experimental data are not sufficiently accurate to decide whether these or Dr. Rav's expressions better represent the facts.

9. *Summary.*

In this paper, the question of fluctuations of dielectric constant of a small volume element of a liquid is discussed with reference to the theories of molecular scattering of light. Reasons are given for concluding that the fluctuations of dielectric constant responsible for scattering cannot be determined by differentiating Lorentz's relation between dielectric constant and density but that the factor $(K+2)/3$ must be omitted from the expression for δK. Revised expressions for the intensity and polarisation of the scattered light are given in terms of the molecular theory.

Gans's phenomenological method of treatment is outlined and discussed and the assumptions underlying it pointed out. If the omission of the $(K+2)/3$ factor of the expression for δK be accepted, Gans's theory and molecular theory lead to identical results.

It is shewn that if the molecules of a liquid are anisotropic, small volume elements must necessarily possess accidental deviations from isotropy; the relation between them, the constants of molecular anisotropy and the Kerr constant of electric double refraction is worked out.

Mr. Krishnan has shown that results of experiments are favourable to the omission of the factor $(\nu^2+2)^2/9$.

It is pointed out that similar arguments should hold in the case of binary liquid mixtures and that the fluctuations of concentration accidentally occurring in such a mixture cannot be assumed to be identical with the changes of

dielectric constant with concentration obtained from experiments on liquids in mass. Revised expressions for scattering are given.

I wish to express my thanks to Prof. C. V. Raman for his kind interest in the work.

SKY-ILLUMINATION AT SUNRISE AND SUNSET.

BY

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Abstract.—Intensities of sky-illumination due to molecular scattering when the sun is on the horizon at a place 2 km. above sea-level are calculated for the wave-lengths 0·45μ, 0·55μ and 0·65μ. The calculated values are in reasonable agreement with the values measured by Dorno at Davos on clear days, but are smaller than those calculated by Gruner. The reason for the discrepancy is explained. The calculations show that the light from the sky when the sun is on the horizon is richer in the longer waves than the normal day-sky. It is argued that we should expect to get a maximum polarisation of sky-light in a direction perpendicular to the sun when he is on the horizon and when we confine ourselves to the red end of the spectrum. Measurements on red light from clear skies at Simla showed values of polarisation as high as 87 per cent. just before sunrise and just after sunset.

INTRODUCTION.

A summary of the principal features of sky-illumination at times of sunrise and sunset as recorded by various observers is given in a convenient form in Pernter's *Meteorologische Optik* and in recent papers by Professors Gruner[1] and Dorno.[2] While a large number of interesting and beautiful phenomena owe their origin to the presence of dust and condensed moisture in the atmosphere, there are other features observable in the clearest weather and at such high levels that the quantity of dust present can be but a very small fraction of that usually present at sea-level. These latter must, from the very circumstances of their occurrence, be capable of explanation by the action of the permanent constituents of the atmosphere.

Some prominent features of sky-illumination in clear weather when the sun is near the horizon.

(1) The sky ceases to have the distinctive blue colour which it has during the day, and becomes grey with a tinge of purple.

(2) A purple counter-glow appears against the sun when he is very near the horizon and gradually rises up as the sun sinks down, being bounded at its lower edge by the greyish-blue earth-shadow. The lower boundary is particularly well-marked when viewed through a red glass. The purple reaches its maximum intensity when the sun is 3° to 4° below the horizon.

(3) The colour of the sky some 5° to 10° above the horizon a few minutes after he sun has gone down, gradually changes as the azimuth of observation is changed, the colours being yellowish white, yellow, ochre, ruddy and steel-blue (colour of the earth-shadow) as we move from the sun to the anti-sun.

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[1] P. Gruner: Beitr. Physik Atmosph., *Leipzig*, **8**, 1919, p. 1 and p. 120.

[2] C. Dorno, Met. Zs., **52**, 1917, p. 153. *See also* F. J. W. Whipple, Article on "Meteorological Optics" in *Dictionary of Applied Physics*, III, p. 522.

(4) The polarisation of the sky in a direction perpendicular to the incident light is a maximum when the sun is about 2° below the horizon.

(5) When the light from the vertical sky is analysed into two components, they are of *distinctly* different colours, the stronger component having a smaller proportion of blue than the weaker.

The origin of sky-illumination.

That the blue of the clear day-sky is due to scattering by air-molecules is well-established. The detailed calculations of Professor L. V. King[1] show that most of the sky-illumination on clear days at Mount Whitney and Mount Wilson is due to this cause. We have therefore *a priori* reason to expect that the main features of the twilight sky on clear days at high-level stations should also be due to the same cause. Calculations by Professor Gruner[2] show that scattering by air molecules can account for the changes of colour of the sky as the sun approaches the horizon. Gruner has calculated the intensities of sky-illumination in different directions in the vertical plane containing the sun, as the zenith distance of the sun changes from 90° to 96° for two wave-lengths 0·55μ and 0·64μ as would be observed from a station 4 km. above sea-level. For convenience of calculation, he divides the atmosphere into four layers 0 to 4 kms., 4 to 12 kms., 12 to 24 kms., and 24 to 84 kms., and assumes a uniform distribution of molecules within each of these layers. The absolute values of the intensities calculated by Gruner are considerably *in excess* of the values observed by Dorno[3] at Davos. The reasons for this appear to be (1) adoption of values of scattering coefficients derived from those of the attenuation coefficients at Mount Whitney, assuming the attenuation to be due solely to molecular scattering and (2) the approximate nature of his method of calculation. In the following paper, a stricter method of calculation is developed and the values of scattering coefficients are calculated by Rayleigh's law; the results show closer agreement with observation, the calculated values being now smaller than the observed; the method also brings out some new points of interest.

Method of calculation.

In the following calculations, atmospheric refraction is neglected, so that the rays are considered horizontal throughout their course. (The effect of refraction is to make an object on the horizon appear to have an altitude of 35′ for an observer at sea-level). Intensities of sky-illumination are calculated for the wave-lengths 0·45μ, 0·55μ and 0·65μ both in the vertical plane containing the sun and also in a perpendicular plane. To get the amount of light received in any direction OP we have to integrate the light scattered by all the molecules lying within a cone of small solid angle $d\omega$ in that direction, making allowance for the attenuation of the light in its passage from the molecules to the observer.

Let φ be the angle between the incident and scattered beams of light (Fig. 1).

I the intensity of illumination at P due to the incident light between the wave-lengths λ and $\lambda + d\lambda$

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[1] L. V. King, *Phil. Trans.* A, **212**, 1913, p. 375.

[2] P. Gruner, Beitr. Physik Atmosph., **8**, 1919, p. 120.

[3] C. Dorno, *Veroff. Pruess. Met. Inst.*, 303, **6**, 1919; also *Met. Zs.*, **36**, 1919, p. 109.

l the distance between the place of observation and P,

n the number of molecules per unit volume at P,

$S\ (1 + cos^2\varphi)$ the scattering coefficient due to a single molecule in a direction making an angle φ with an incident unpolarised beam of light, and nk the attenuation coefficient appropriate to density n. I, S, and k refer to the same wave-length. Then the intensity of light at O between the wave-lengths λ and $\lambda + d\lambda$ due to the scattered light from an element of volume $l^2\ d\omega\ dl$ at P will be

$$n\ S\ I\ (1 + cos^2\varphi)\ Exp\ [-k \int ndl\ ]\ dl\ d\omega\ d\lambda \qquad (1).$$

and from all the particles within the cone, it will be

$$d\omega\ d\lambda \int_o^L n\ S\ I\ (1 + cos^2\varphi)\ Exp\ [-k \int ndl\ ]\ dl \qquad (2).$$

where L is the distance corresponding to the limit of the atmosphere.

Now, I itself varies with the position of the point P, since the original incident light has already been filtered through a certain length of the atmosphere. (*See* fig. 2.)

If ds denotes an element of path of the incident ray in the atmosphere before reaching P, the intensity of illumination at P will be $I_o\ exp\ [-k \int nds\ ]$ where I_o is the intensity outside the atmosphere and the integration is taken from outside the atmosphere to P, and (2) will become $d\omega\ d\lambda \int_o^L n\ S\ I_o\ (1 + cos^2\varphi)\ Exp\ [-k \int ndl + nds.]\ dl$ (3).

The numerical computation of this quantity involves

(1) a knowledge of the variation of n with height r above sea-level

(2) the conversion of the integrals into appropriate ones involving r as the variable, and

(3) evaluation of the integrals graphically.

(1) The values of n used in the following calculations and given in Table I are, up to a height of 20 km., based on the data of pressure and temperature given by W. H. Dines[1] as average values for the free atmosphere over Europe, and above 20 km., calculated on the assumption of isothermal conditions according to the equation $-dp = p\ dh/h$. Heights above 50 km. are neglected and uniformity of composition is assumed throughout.

TABLE 1.

h in kilometres.	T in degrees absolute.	p in millibars.	$n \times 10^{-19}$.
0	281	1014	2·63
1·0	277	899	2·37
2·0	272	794	2·13
4·0	261	614	1·72
5·0	255	538	1·54
8·0	233	353	$1{\cdot}10_5$

[1] W. H. Dines; Geophys Mem., Met. Office, *London*, **13**, p. 63.

TABLE 1—*contd.*

h in kilometres.	T in degrees absolute.	p in millibars.	$n \times 10^{-19}$.
10·0	222	262	0·860
12·0	219	192	$0{\cdot}64_2$
15·0	219	120	$0{\cdot}40_0$
20·0	219	55	$0{\cdot}18_3$
30·0	219	11·5	0·038
40·0	219	2·4	0·008
50·0	219	0·5	0·0018

(2) dl and ds are expressed in terms of dr in the following way.

In figure 3, C is the centre of the earth, O the position of the observer and P the point at which we want dl and ds. Let R be the radius of the earth, h_1 the height of the observer above sea-level, ξ the zenith distance of P, and θ the angle at the centre of the earth between the vertical through the observer and C P.

Then $\frac{dr}{dl} = cos\ (\xi - \theta)$

and $\frac{sin\ (\xi - \theta)}{sin\ \xi} = \frac{R + h_1}{R + r}$ where r is the height of P above sea-level.

$$\left(\frac{dr}{dl}\right)^2 = 1 - sin^2\ (\xi - \theta)$$

$$= 1 - \frac{(R + h_1)^2}{(R + r)^2}\ sin^2\ \xi$$

$$\therefore\ dl = dr\ \frac{R + r}{[\ (R + r)^2 - (R + h_1)^2\ sin^2\ \xi\ ]^{\frac{1}{2}}} \qquad (4).$$

$$\frac{ds}{dr} = cosec\ \theta = \frac{R + r}{s} = \frac{R + r}{[\ (R + r)^2 - (R + h)^2\ ]^{\frac{1}{2}}} \doteqdot \frac{\sqrt{\ R}}{\sqrt{2\ (r - h)}} \qquad (5).$$

where h is the height of Q above the earth.

When P coincides with Q, $r = h$ and the denominator of (5) becomes zero. If, however, we integrate ds in the immediate neighbourhood of Q between the limits $r = h$ and $r = r_1$, we get :

$$S_1^2 = 2\ R\ (r_1 - h) \text{ or } S_1 = \sqrt{2\ R\ (r_1 - h)} \qquad (6)$$

The integrals $\int ndl$ and $\int nds$ have to be taken between the appropriate limits. It is convenient to split up $\int_T^P nds$ into two parts, (1) $\int_T^Q nds$ from outside the atmosphere to a point Q vertically overhead and (2) $\int_Q^P nds$ from Q to P. (*See* fig. 2.) These may be distinguished by the symbols $\int nds_1$ and $\int nds_2$ respectively.

(3) We also require the coefficients of scattering and attenuation for different wavelengths. Their values are given in Table 2. The fraction of the incident light scattered by 1 c.c. of air at N. T. P. per unit solid angle in a direction perpendicular to the incident beam is calculated by Rayleigh's formula $\pi^2\ (\upsilon^2 - 1)^2 / 2n\lambda^4$, where υ is the refrac-

tive index of the gas for the particular wave-length, and n the number of molecules per cubic centimetre.

TABLE 2.

λ	S	Attenuation Coefficient.	
		At Mt. Wilson.	At Mt. Whitney.
0·39μ	$2{\cdot}69 \times 10^{-8}$	0·365	0·270
0·45μ	$1{\cdot}515 \times 10^{-8}$	0·223	0·101
0·50μ	$0{\cdot}994 \times 10^{-8}$	0·153	0·105
0·55μ	$0{\cdot}679 \times 10^{-8}$	0·132	0·0866
0·60μ	$0{\cdot}479 \times 10^{-8}$	0·117	0·0683
0·65μ	$0{\cdot}348 \times 10^{-8}$		0·0550

The coefficients of attenuation are obtained from the Smithsonian transmission coefficients measured at Mount Wilson and Mount Whitney.[1] Since the pressures at these two places are different, being 61·7 cm and 44·67 cm respectively, the coefficients of attenuation refer to passage through different thicknesses of atmosphere. They are reduced so as to refer to the same number of molecules by multiplying by $76/(p \times 8{\cdot}0 \times 2{\cdot}705)$ where p is the pressure at the station in centimetres of mercury. Since the height of the "homogeneous" atmosphere is 8·0 kilometres and since each c.c. of air at N. T. P. contains $2{\cdot}705 \times 10^{19}$ molecules, this reduced value corresponds to the passage of a beam of light of unit area of cross section over 10^{24} molecules.[2] If the attenuation is due solely to air molecules, the reduced values for different wave-lengths should be the same when calculated from the transmission coefficient of either station. That this is approximately so will be clear from the following table.

TABLE 3.

λ	Mount Wilson $p_1 = 61{\cdot}7$ cm.		Mount Whitney, $p_2 = 44{\cdot}67$ cm.	
	K_1	$\frac{K_1 \times 76}{p_1 \times 2{\cdot}705 \times 8{\cdot}0}$	K_2	$\frac{K_2 \times 76}{p_2 \times 2{\cdot}705 \times 8{\cdot}0}$
0·39μ	0·365	0·0208	0·270	0·0212
0·45μ	0·223	0·0127	0·161	0·0127
0·50μ	0·153	$0{\cdot}0087_1$	0·105	$0{\cdot}0082_5$
0·55μ	0·132	$0{\cdot}0075_1$	$0{\cdot}086_6$	0·0068
0·60μ	0·117	$0{\cdot}0066_7$	$0{\cdot}068_3$	0·0054
0·65μ	..	..	0·055	0·0043
0·70μ	0·060	0·0034	0·045	0·0035

[1] L. V. King, *loc. cit.*

[2] This is not strictly correct, as the "effective" temperature of the atmosphere is not exactly 0° C. The approximation is, however, close enough for our present purposes.

In what follows, we shall adopt the average of the values in columns 3 and 5 and calculate the intensities of illumination of the clear sky for wave-lengths 0·45μ, 0·55μ and 0·65μ as observed at a place 2 km. above sea-level for azimuths 0°, 90° and 180° and various zenith distances.

The different steps of the calculation are as follow :—

(i) $\int nds_1$ *for different heights.*—A table is prepared showing values of r increasing from $h = 0{\cdot}5$ km. to $h = 50$ km. (column 1), the corresponding values of n (column 2), and the calculated values of $n\sqrt{R}/\sqrt{2(r-h)}$ (column 3). The numbers in column 3 are then plotted on graph paper against those in column 1 and the integral $\int_{h+0{\cdot}5}^{50} nds_1$ obtained. This may be done in any number of convenient steps. To obtain $\int_{h}^{h+0{\cdot}5} nds_1$ relation (6) is used, r_1-h being equal to $\frac{1}{2}$ km. and n being taken to be the mean of the values at h and $h + 0{\cdot}5$ km.

TABLE 4.

Example.
$h = 12$ km.

r in kilometres.	$n \times 10^{-19}$	$\frac{n\sqrt{R}}{\sqrt{2(r-h)}} \times 10^{-19}$
12·5	0·59	47·1
13	0·55	31·0
15	0·40	13·0
18	0·24	5·5
22	0·138	2·46
27	0·063	0·92
32	$0{\cdot}026_2$	0·33
42	0·0060	0·062
52	0·0014	0·0125

From graphs, $\int_{13}^{20} nds = 0{\cdot}75 \times 10^{26}$; $\int_{20}^{50} nds = 0{\cdot}192 \times 10^{26}$ and by calculation $\int_{12}^{12{\cdot}5} nds = 0{\cdot}49 \times 10^{26}$ and $\int_{12{\cdot}5}^{13} nds = 0{\cdot}195 \times 10^{26}$. Therefore, $\int_{12}^{50} nds = 1{\cdot}63 \times 10^{26}$. Similar calculations are carried out for different values of h and Table 5 is prepared.

TABLE 5.

$\int nds_1$ *for different heights.*

Height in kilometres.	0	3	5	8	12	20	30	40
$\int nds_1 \times 10^{-26}$ . .	8·43	5·49	4·24	2·93	1·63	0·484	0·094	0·020

(ii) For any chosen value of ξ, $\frac{dl}{dr}$ and $n\frac{dl}{dr}$ are calculated from (4) for various values of r; by plotting $n\frac{dl}{dr}$ against r and integrating graphically between appropriate limits, we get $\int n\frac{dl}{dr}\,dr$ or $\int ndl$ between the observer and any position of P.

(iii) In figure 3, the height h of Q above sea-level is given by $2R(r-h) = PQ^2 = (h-h_1)^2 \tan^2 \xi$. The values of h for different values of r when $\xi = 85°$ are given in table 6. It will be seen that h and r are appreciably different from each other only at large heights where the density is small. We may therefore take the average of the values of n at heights h and r and multiply it by PQ in order to obtain $\int nds_2$ at height h.

TABLE 6.

$\xi = 85°$, $h_1 = 2$ km.

r in kilomefres	5	8	10	15	20	30	40	50
h in kilometres	4·9	7·7	9·5	13·7	17·5	24·7	31·2	37·5

(iv) From values obtained as in (i), (ii) and (iii), $Exp\,[-k\int(ndl + nds_1 + nds_2)]$ is calculated for different values of l and hence of r, and the quantity $I_\circ S(1 + \cos^2\varphi)\,d\omega\,d\lambda \int_2^{50} n\frac{dl}{dr}\,Exp\,[-k\,(ndl + nds + ndr)]\,dr$ evaluated by graphical integration.

Example

$\xi = 80°$, Azimuth $= 180°$.

TABLE 7.

Height in kilometres.	$\int nds_1$	$\int nds_2$	$\int ndl$	$\int (nds_1 + nds_2 + ndl)$.
2	$6{\cdot}4 \times 10^{26}$	..	..	$6{\cdot}4 \times 10^{26}$
5	$4{\cdot}26 \times 10^{26}$	$0{\cdot}26 \times 10^{26}$	$0{\cdot}31 \times 10^{26}$	$4{\cdot}83 \times 10^{26}$
8	$2{\cdot}95 \times 10^{26}$	$0{\cdot}37 \times 10^{26}$	$0{\cdot}53 \times 10^{26}$	$3{\cdot}85 \times 10^{26}$
10	$2{\cdot}27 \times 10^{26}$	$0{\cdot}38 \times 10^{26}$	$0{\cdot}64 \times 10^{26}$	$3{\cdot}29 \times 10^{26}$
15	$1{\cdot}15 \times 10^{26}$	$0{\cdot}29 \times 10^{26}$	$0{\cdot}82 \times 10^{26}$	$2{\cdot}26 \times 10^{26}$
20	$0{\cdot}53 \times 10^{26}$	$0{\cdot}19 \times 10^{26}$	$0{\cdot}90 \times 10^{26}$	$1{\cdot}62 \times 10^{26}$
30	$0{\cdot}10 \times 10^{26}$	$0{\cdot}07 \times 10^{26}$	$0{\cdot}95 \times 10^{26}$	$1{\cdot}12 \times 10^{26}$
40	$0{\cdot}02 \times 10^{26}$	$0{\cdot}02 \times 10^{26}$	$0{\cdot}96 \times 10^{26}$	$1{\cdot}00 \times 10^{26}$
50	..	..	$0{\cdot}96 \times 10^{26}$	$0{\cdot}96 \times 10^{26}$

TABLE 8.

$\xi = 80^c$, azimuth 180^c, $\lambda = 0{\cdot}45\mu$.

Height in kilometres.	$Sn \frac{dl}{dr}$	$k\int(nds_1 + nds_2 + ndl)$.	$Exp\,[-k\int(nds_1 + nds_2 + ndl)$.	Col. (2) × Col. (4)
2	$6{\cdot}87 \times 10^{-8}$	8·12	0·0003	$\cdot0021 \times 10^{-8}$
5	$4{\cdot}88 \times 10^{-8}$	6·13	·0022	$\cdot0108 \times 10^{-8}$
8	$3{\cdot}46 \times 10^{-8}$	4·88	·0076	$\cdot0264 \times 10^{-8}$
10	$2{\cdot}67 \times 10^{-8}$	4·17	·0155	$\cdot0415 \times 10^{-8}$
15	$1{\cdot}213 \times 10^{-8}$	2·87	·0567	$\cdot0640 \times 10^{-8}$
20	$0{\cdot}543 \times 10^{-8}$	2·05	·129	$\cdot0700 \times 10^{-8}$
30	$0{\cdot}109 \times 10^{-8}$	1·42	·242	$\cdot0263 \times 10^{-8}$
40	$0{\cdot}022 \times 10^{-8}$	1·27	·281	$\cdot0061 \times 10^{-8}$
50	$0{\cdot}0048 \times 10^{-8}$	1·22	·295	$\cdot0014 \times 10^{-8}$

The values in the last column are integrated from 2 to 50 km. and multiplied by $1 + sin^2\xi$, $sin^2\xi$ being equal to $cos^2\varphi$ when the incident rays are horizontal. Similar calculations are carried out for the other two wave-lengths $0{\cdot}55\mu$ and $0{\cdot}65\mu$. For azimuth 0^c, $\int(nds_1 + nds_2 + ndl)$ should be replaced by $\int(nds_1 - nds_2 + ndl)$ and for azimuth 90^c by $\int(nds_1 + ndl)$.

Results.

The following table gives the values of the intensities of illumination in different directions.

TABLE 9.

λ	Intensity of scattered light per unit solid angle. / Intensity of incident sunlight.				
	$\xi = 0°$.	$\xi = 45°$.	$\xi = 60°$.	$\xi = 80°$.	$\xi = 85°$.
Azimuth 0°—					
0·45μ . .	..	$1{\cdot}81 \times 10^{-3}$	$2{\cdot}65 \times 10^{-3}$	$4{\cdot}94 \times 10^{-3}$	$4{\cdot}20 \times 10^{-3}$
0·55μ . .	..	$1{\cdot}66 \times 10^{-3}$	$2{\cdot}67 \times 10^{-3}$	$6{\cdot}28 \times 10^{-3}$	$8{\cdot}18 \times 10^{-3}$
0·65μ . .	..	$1{\cdot}46 \times 10^{-3}$	$2{\cdot}34 \times 10^{-3}$	$6{\cdot}52 \times 10^{-3}$	$9{\cdot}76 \times 10^{-3}$
Azimuth 90°—					
0·45μ . .	$0{\cdot}90 \times 10^{-3}$	$1{\cdot}16 \times 10^{-3}$	$1{\cdot}40 \times 10^{-3}$	$1{\cdot}89 \times 10^{-3}$	$1{\cdot}12 \times 10^{-3}$
0·55μ . .	$0{\cdot}79 \times 10^{-3}$	$1{\cdot}07 \times 10^{-3}$	$1{\cdot}42 \times 10^{-3}$	$2{\cdot}70 \times 10^{-3}$	$2{\cdot}80 \times 10^{-3}$
0·65μ . .	$0{\cdot}69 \times 10^{-3}$	$0{\cdot}95 \times 10^{-3}$	$1{\cdot}28 \times 10^{-3}$	$2{\cdot}87 \times 10^{-3}$	$3{\cdot}89 \times 10^{-3}$
Azimuth 180°—					
0·45μ . .	..	$1{\cdot}61 \times 10^{-3}$	$2{\cdot}24 \times 10^{-3}$	$2{\cdot}84 \times 10^{-3}$	$1{\cdot}23 \times 10^{-3}$
0·55μ . .	..	$1{\cdot}55 \times 10^{-3}$	$2{\cdot}30 \times 10^{-3}$	$4{\cdot}39 \times 10^{-3}$	$3{\cdot}93 \times 10^{-3}$
0·65μ . .	..	$1{\cdot}38 \times 10^{-3}$	$2{\cdot}18 \times 10^{-3}$	$4{\cdot}97 \times 10^{-3}$	$6{\cdot}22 \times 10^{-3}$

It is evident from the above table that the composition of sky-light when the sun is on the horizon is quite different from that of the normal day-light sky. In the zenith, where the relative proportion of short waves is the largest, the ratio of the blue (0·45μ) to the red (0·65μ) is only 1·3 times that in the original light, while according to the inverse fourth power law, the ratio would be 4·3. This accounts for the well marked change of colour which is easily noticeable at times of sunrise and sunset. As we move from the zenith to the horizon the proportion of blue decreases still more, the ratio blue to red becoming 0·66 at a zenith distance of 80° in a direction perpendicular to the sun's rays and 0·57 against the sun. The more marked reddening on increase of azimuth is in agreement with observation.

The purple of the counterglow is a composite colour containing all the colours of the spectrum with a preponderance of red.

The best observational data available for comparison with the above are those obtained by Professor Dorno at Davos (1590 metres above sea-level) in Switzerland. His relative measurements at different parts of the sky were made with Weber's polarisation photometer and measurements at the zenith with the same author's milk-glass photometer.[1] Red and green filters were used and corrections applied for the composite character of the light depending on the ratio green/red. Dorno has given his results[2] in terms of the brightness of an absolutely white, matt surface illuminated with an intensity of one metre-candle, the brightness of the sun outside the earth's atmosphere[3] in terms of the same unit being 7660×10^6. The values given in the following table are the annual means of the brightness of sky in different directions in terms of the brightness of the sun outside the earth's atmosphere.

[1] A description of the instrument is given in the *Dictionary of Applied Physics*, IV, p. 440.

[2] Table 25*a*. "Himmelshelligkeit, etc.", *l. c.*

[3] "Himmelshelligkeit, etc.", p. 54.

TABLE 10.*

Brightness of sky / Brightness of sun.	Azimuth.	$\xi = 0°$.	$\xi = 45°$.	$\xi = 60°$.	$\xi = 80°$.	$\xi = 85°$.
Calculated—						
·45μ . . .		$0{\cdot}61 \times 10^{-7}$	$1{\cdot}23 \times 10^{-7}$	$1{\cdot}80 \times 10^{-7}$	$3{\cdot}35 \times 10^{-7}$	$2{\cdot}85 \times 10^{-7}$
·55μ . . .		$0{\cdot}54 \times 10^{-7}$	$1{\cdot}12 \times 10^{-7}$	$1{\cdot}81 \times 10^{-7}$	$4{\cdot}25 \times 10^{-7}$	$5{\cdot}5 \times 10^{-7}$
·65μ . . .	0°	$0{\cdot}47 \times 10^{-7}$	$0{\cdot}99 \times 10^{-7}$	$1{\cdot}58 \times 10^{-7}$	$4{\cdot}42 \times 10^{-7}$	$6{\cdot}6 \times 10^{-7}$
Calculated by Gruner—						
·55μ . . .		$1{\cdot}06 \times 10^{-7}$	$2{\cdot}28 \times 10^{-7}$	$3{\cdot}60 \times 10^{-7}$	$9{\cdot}3 \times 10^{-7}$	$14{\cdot}4 \times 10^{-7}$
·64μ . . .		$0{\cdot}97 \times 10^{-7}$	$1{\cdot}99 \times 10^{-7}$	$3{\cdot}40 \times 10^{-7}$	$11{\cdot}2 \times 10^{-7}$	$16{\cdot}7 \times 10^{-7}$
Observed Dorno . .		$0{\cdot}63 \times 10^{-7}$	$1{\cdot}51 \times 10^{-7}$	$3{\cdot}97 \times 10^{-7}$	$7{\cdot}8 \times 10^{-7}$	..
Calculated—						
·45μ . . .		$0{\cdot}61 \times 10^{-7}$	$0{\cdot}77 \times 10^{-7}$	$0{\cdot}95 \times 10^{-7}$	$1{\cdot}28 \times 10^{-7}$	$0{\cdot}76 \times 10^{-7}$
·55μ . . .		$0{\cdot}54 \times 10^{-7}$	$0{\cdot}73 \times 10^{-7}$	$0{\cdot}96 \times 10^{-7}$	$1{\cdot}83 \times 10^{-7}$	$1{\cdot}90 \times 10^{-7}$
·65μ . . .	90°	$0{\cdot}47 \times 10^{-7}$	$0{\cdot}63 \times 10^{-7}$	$0{\cdot}87 \times 10^{-7}$	$1{\cdot}95 \times 10^{-7}$	$2{\cdot}64 \times 10^{-7}$
Calculated by Gruner—						
·55μ . . .		$1{\cdot}06 \times 10^{-7}$	..	..	..	..
·64μ . . .		$0{\cdot}97 \times 10^{-7}$	..	..	..	..
Observed Dorno . .		$0{\cdot}63 \times 10^{-7}$	$1{\cdot}04 \times 10^{-7}$	$1{\cdot}59 \times 10^{-7}$	$2{\cdot}64 \times 10^{-7}$	..
Calculated—						
·45μ . . .		$0{\cdot}61 \times 10^{-7}$	$1{\cdot}09 \times 10^{-7}$	$1{\cdot}52 \times 10^{-7}$	$1{\cdot}92 \times 10^{-7}$	$0{\cdot}83 \times 10^{-7}$
·55μ . . .		$0{\cdot}54 \times 10^{-7}$	$1{\cdot}05 \times 10^{-7}$	$1{\cdot}56 \times 10^{-7}$	$2{\cdot}98 \times 10^{-7}$	$2{\cdot}66 \times 10^{-7}$
·65μ . . .	180°	$0{\cdot}47 \times 10^{-7}$	$0{\cdot}93 \times 10^{-7}$	$1{\cdot}48 \times 10^{-7}$	$3{\cdot}36 \times 10^{-7}$	$4{\cdot}22 \times 10^{-7}$
Calculated by Gruner—						
·55μ . . .		$1{\cdot}06 \times 10^{-7}$	$2{\cdot}12$	$3{\cdot}30 \times 10^{-7}$	$7{\cdot}3 \times 10^{-7}$	$7{\cdot}7 \times 10^{-7}$
·64μ . . .		$0{\cdot}97 \times 10^{-7}$	$1{\cdot}98$	$3{\cdot}15 \times 10^{-7}$	$8{\cdot}3 \times 10^{-7}$	$11{\cdot}6 \times 10^{-7}$
Observed Dorno . .		$0{\cdot}63 \times 10^{-7}$	$1{\cdot}04 \times 10^{-7}$	$1{\cdot}86 \times 10^{-7}$	$3{\cdot}35 \times 10^{-7}$	..

* The calculated values given in the above table will be raised by a small amount if we add to the polarised scattering contemplated in the Rayleigh law the additional unpolarised scattering due to the anisotropy of the molecules. The expression for the fraction of light scattered per unit angle by 1 c.c. of air in a direction making an angle φ with the incident light, will, if this is included, become $\frac{\pi^2 (\upsilon^2-1)^2}{2n\lambda^4} \frac{6(1+\rho)}{6-7\rho} \left(1 + \frac{1-\rho}{1+\rho} cos^2 \varphi\right)$ instead of $\frac{\pi^2 (\upsilon^2-1)^2}{2n\lambda^4} (1+cos^2\varphi)$ where ρ is the ratio of the minimum to the maximum intensity when the light scattered perpendicular to the incident beam is examined by means of a nicol prism. The values of ρ for dustfree air determined experimentally is 4·5 per cent. The computed values of sky-brightness will be increased in the following ratios at different zenith distances :

——	0°	45°	60°	80°	85°
Sky-Brightness taking into account unpolarised scattering / Sky-Brightness taking into account only Rayleigh scattering	1·10	1·07	1·06	$1{\cdot}05_5$	$1{\cdot}05_5$

For comparison, the values calculated by Gruner for wave-lengths $5{\cdot}5 \times 10^{-5}$ cm. and $6{\cdot}4 \times 10^{-5}$ cm. are also given, after being reduced to the same units as are here used. It will be noticed that Gruner's values are much higher than those calculated in this paper. The main reason for this difference is the adoption by Gruner of scattering coefficients at Mount Whitney on the assumption that the attenuation is solely due to scattering. Equation (3) shows that the calculated brightness of the sky in any direction will be proportional to the value of S. The following table gives the values of scattering coefficients calculated according to Rayleigh's law and adopted in this paper and the values calculated from the attenuation coefficients at Mount Whitney.

Wave-lengths.	Scattering coefficients.	
	According to Rayleigh's law.	Calculated from the extinction coefficients at Mount Whitney.
$4{\cdot}5 \times 10^{-5}$ cm.	$1{\cdot}52 \times 10^{-8}$	$2{\cdot}05 \times 10^{-8}$
$5{\cdot}5 \times 10^{-5}$ cm.	$0{\cdot}679 \times 10^{-8}$	$1{\cdot}10 \times 10^{-8}$
$6{\cdot}5 \times 10^{-5}$ cm.	$0{\cdot}348 \times 10^{-8}$	$0{\cdot}70 \times 10^{-8}$

It is obvious that the adoption of values in column (3) instead of those in column (2) would lead to much higher values for the calculated brightness.

Other less important reasons for the difference are to be found in (1) that Gruner has calculated the brightness of the sky as seen from a point 4 km. above sea-level and (2) the difference in the methods of calculation.

Taking the calculated values of the intensities near $0{\cdot}55\mu$ (the most luminous part of the spectrum) as a rough guide, the differences from the calculated values are such as can be explained by the added scattering and extinction caused by the presence of dust in the atmosphere.

Dorno states that the more transparent the sky, the darker is the region of the sky on the side of the sun and the brighter the region against the sun. The contrast between the two regions was larger in summer and autumn than in winter and spring; at a distance of 10° to 30° from the sun, the excess of the brightness of the summer sky over the annual mean and the defect of brightness of the spring sky were as much as 50 per cent. The agreement with calculated values would therefore be improved if the values observed in winter and spring are alone considered.

In the above calculations, we have neglected the effect of secondary scattering. There is no doubt that this part is not negligible as is evidenced by the blue colour of the sky in the earth-shadow below the lower limit of the purple counterglow and the absence of colour-match of the two components when the light from the vertical sky is analysed by a double image prism. We should expect the effect of the secondary scattering to be much more serious for the shorter wave-lengths than for the longer ones. Not only is this due to the λ^{-4} law; it is also due to the way in which different layers of the atmosphere contribute to the total illumination. This will be clear from figures 5 and 6. Figure 5 represents the intensities of illumination due to a layer of the atmos-

phere 1 cm. in thickness and subtending a unit solid angle at the observer's eye for different heights of the layer and for three different wave-lengths. The peak of the curve occurs at a greater height for the shorter wave-lengths. Thus the heights of the layers which contribute the maximum effect for wave-lengths 0·45μ, 0·55μ and 0·65μ are 18 km., 12 km., and 10 km., respeetively. Figure 6 represents the intensities due to a layer 1 cm. in *radial* thickness coming from a direction perpendicular to the sun's rays and at a zenith distance of 80°. The peaks of the curve occur at heights 15 km., 12 km. and 9 km. It will also be noticed that the curve for 0·45μ is flatter than the one for 0·55μ and this again flatter than that for 0·65μ. In a case like this where most of the scattered light has its origin in a comparatively thin layer, the self-illumination will not be so prominent as when the illumination is diffused over a much larger th ckness. As a result of secondary scattering, while the values of intensity in table 10 would be fairly correct for the longest wave-lengths, they will fall short of the actual illumination for the shorter waves.

Polarisation of sky-light in different regions of the spectrum when the sun is just below the horizon.

It is well known that the polarisation of the zenith sky on clear days increases as the sun gets farther from the zenith and that the maximum value of the polarisation is observed when the sun is 1° or 2° below the horizon. This is clearly due to the very small contribution to the sky-illumination made by the lower dusty atmosphere at that time, and also to the diminution of self-illumination and earth-illumination in the atmosphere. From the way in which different layers of atmosphere contribute to the sky-illumination in different regions of the spectrum, it may be expected that the polarisation in a direction perpendicular to the sun's rays should be greatest for those wave-lengths for which the effect of self-illumination is least, that is, for the longest waves. Observations made by the writer during the winter of 1925-26 in the exceptionally favourable atmosphere of Simla confirm this, the polarisation of the zenith sky being distinctly greater for the red than for the blue. In a recent paper, N. N. Kalitin of Pawlawsk,[1] has recorded that under the best conditions of transparency of the atmosphere, the polarisation is always greater in the red than in the blue, and that as the sun sinks down, the former increases more rapidly than the latter. We may expect that the effect of secondary illumination would be a minimum if we take observations about the time of sunrise and sunset in red light at a point in the heavens a few degrees above the horizon perpendicular to the sun's rays where, as the curves in figure 5 indicate, the quantity of red light coming from the sky is greater than that of the blue and is confined to a layer of smaller thickness and nearer the surface of the earth. This conclusion has also been confirmed by observation. The polarisation measured with a double image prism and nicol a few degrees above the southern horizon at Simla with a *deep red* filter, showed that on clear days, the polarisation was distinctly larger than on the zenith, the value on many occasions going up to 87 per cent. (corresponding to a depolarisation of 7 per cent.) thus closely approaching the value of the polarisation of the transversely

[1] N. N. Kalitin; *Met. Zs.*, 43, 1926, p. 132.

scattered light for pure air. The maximum polarisation (also measured with a deep red filter) near the zenith was about 3 per cent. lower.[1] We can form an approximate estimate of the intensity of self-illumination if we assume that on clear days, the excess of depolarisation over what is to be expected in consequence of the anisotropy of the molecules is due to this cause. Now, in very clear weather, the light from the zenith sky shows a depolarisation of 9 to 11 per cent. when the sun is on or just near the horizon. Let us take 10 per cent. as a mean value. If there were only primary scattering, the depolarisation of the light from the zenith sky will be 4·5 per cent. If we call this ratio B/(A + B) and if we assume the self-illumination to be unpolarised $0{\cdot}10 = \frac{B + X}{A + B + X}$ where 2 X is the intensity due to self-illumination. Hence $\frac{2X}{A + 2B + 2X} = 10$ per cent. Thus the intensity due to self-illumination is nearly 10 per cent. of the total intensity.

SUMMARY.

(1) Some features of sky-illumination at sunrise and sunset which are observable in the clearest weather at high-level stations are pointed out.

(2) The previous work of Gruner on the calculation of sky-illumination when the sun is near the horizon is reviewed and a more rigorous method of calculating the intensities when the sun is on the horizon worked out.

(3) Intensities of sky-illumination are calculated for different portions of the sky when the sun is on the horizon for the wave-lengths 0·45μ, 0·55μ, and 0·65μ.

(4) The results explain the changes of colour of the sky near sunrise and sunset The calculated values are of the same order as the values of brightness observed by Dorno at Davos, but are generally smaller.

(5) It is pointed out that the way in which different layers of the atmosphere contribute towards twilight illumination depends on the wave-lengths, the shorter wave-lengths coming more from the higher layers.

(6) The polarisation of sky-light perpendicular to the sun's rays when the sun is 1° to 2° below the horizon is greater for red rays than for the blue. The greatest polarisation is observed in an azimuth of 90° a few degrees above the horizon, isolating red light alone by means of a deep red filter. The results are believed to be due to the smaller influence of self-illumination for the longer rays and to the fact that these rays originate in a comparatively thinner layer and nearer the surface of the earth.

The maximum value of the polarisation observed at Simla in very clear weather during the winter of 1925-26 in red light was 87 per cent. This value was reached on many days.

The writer hopes to extend the computation of sky brightness for positions of the sun below the horizon.

The author's thanks are due to Professor C. V. Raman for his interest in the work. The double image prism and nicol with which sky polarisation measurements were made were kindly lent by him.

[1] J. J. Tichanowsky (*Met. Zs.*, 43, 1926, p. 154) has recently obtained a maximum value for the polarisation of the zenith sky of 84·7 per cent. at Ai Petri (1180 metres above sea-level).

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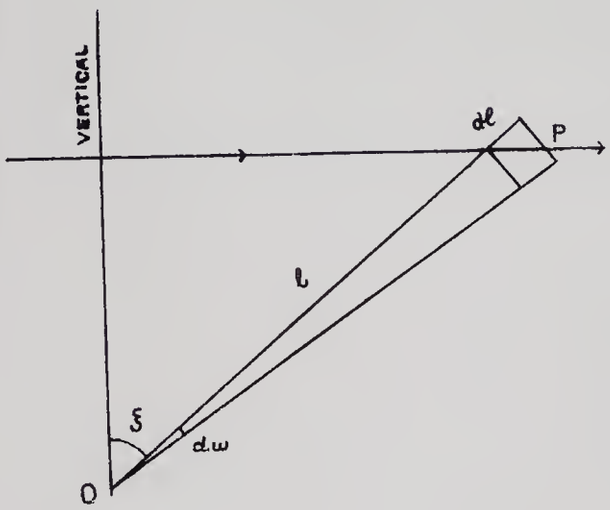

FIG. 1

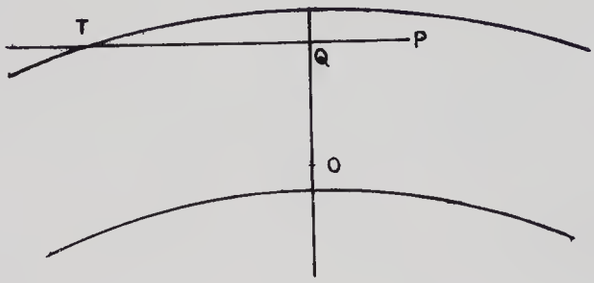

FIG. 2

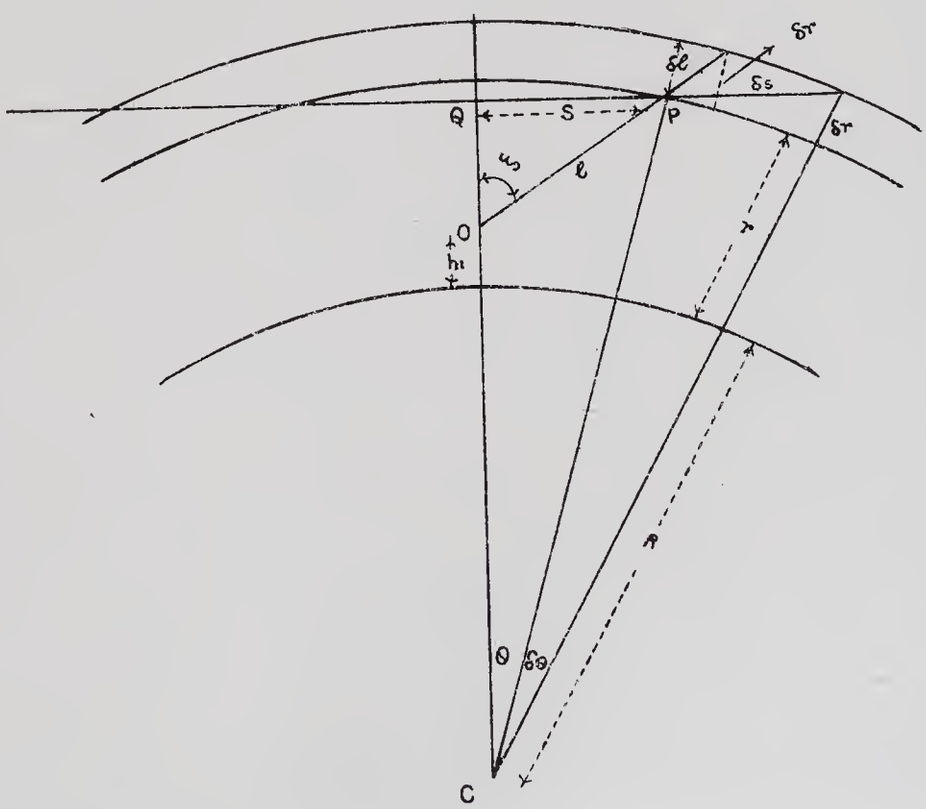

FIG. 3

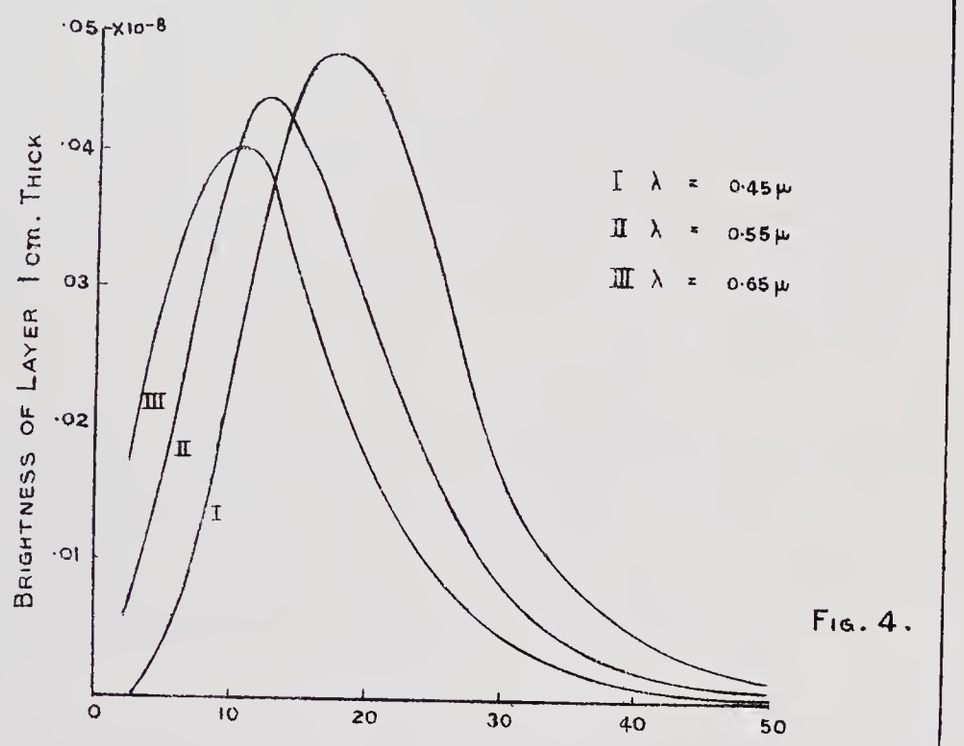

FIG. 4.

BRIGHTNESS OF DIFFERENT LAYERS OF THE ZENITH SKY.

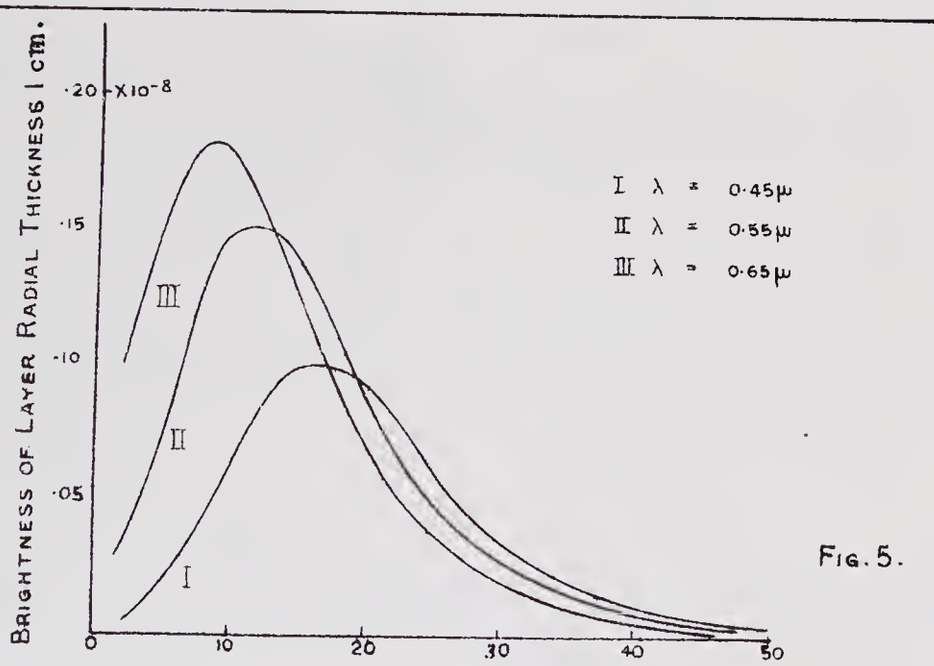

FIG. 5.

BRIGHTNESS OF DIFFERENT LAYERS OF ATMOSPHERE OF RADIAL THICKNESS 1 CM. IN DIRECTION $\zeta = 80^\circ, \alpha = 90^\circ$

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ON THE INTENSITY AND POLARISATION OF THE LIGHT FROM THE SKY DURING TWILIGHT

By J. V. Dave and K. R. Ramanathan, F.A.Sc.

Received December 24, 1955

1. Introduction

The object of this paper is to present the results of some new homogeneous measurements of the brightness of the clear zenith sky taken at Mt. Abu (24° 26′ N; 72° 43′ E) with a photon multiplier and six narrow band filters for different values of solar depression from 0° to 20° together with some measurements of polarisation, discuss the results in the light of our present knowledge of the upper atmosphere and attempt on broad lines an explanation of the optical phenomena observed during the transition between day and night.

2. Experimental Arrangements

An R.C.A. photomultiplier 931–A, selected for small dark current, was used with an A.C. operated D.C. power-supply stabilised by a degenerative type of electronic regulation. The photomultiplier output current was amplified by a balanced-bridge stabilised D.C. amplifier. The sensitivity of the amplifier could be changed successively by factors of about 10 by introducing different resistances varying from 10^3 to 10^8 ohms in its grid circuit. The exact scaling factor from one stage to the next was determined by illuminating the photocathode by a beam of constant intensity and noting the reading in each successive stage. No attempt was made to measure the absolute values of the intensities; only relative intensities were determined. For values of output current less than 400 microamperes, the current was found to be proportional to the intensity of light falling on the photocathode. For higher outputs, the correction due to the non-linearity of the variation of output against input voltage was measured and applied. The effect of varying the orientation of the plane of polarisation of the incident beam on the sensitivity of the photomultiplier was tested and found to be negligible.

Suitable optical filters were used to transmit different parts of the spectrum. The components and characteristics of the filters are shown in Table I. The figures take into account the spectral sensitivity of the photomultiplier. It will be noted that with the green, yellow and red filters, the effective transmissions are about 200 A centred approximately at the respective lines of the airglow spectrum.

Proc. Ind. Acad. Sci. A 43, 67–78, 1956.

TABLE I

Components and effective transmissions of optical filters when used with RCA Photomultiplier 931 *A*

Brief name for filter	Components	Half band-width of transmission	Maximum transmission
U	Chance OX 1	3300–3850	3700–32%
V	Chance OV 1	3640–4050	3850–44%
B	Chance OY 18 and OB 10 ..	4350–4800	4600–9½%
G	I.F. *plus* ON 16 *plus* Plastic Yellow	5530–5750	5600–3½%
Y	I.F. *plus* Chance OY 1	5800–6000	5870–2%
R	I.F. *plus* Plastic Red	6150–6400	6300–1%
J	Polaroid	4000–5500	4600–40%

I. F. stands for interference filter obtained from Messrs. Barr and Stroud.

For the measurement of polarisation, a polaroid of type J was placed in the path of the radiation so as to measure (1) the intensity I_R of the component perpendicular to the sun's meridian and (2) the intensity I_L of the component parallel to it. Both the intensities were measured within a time interval of 5 seconds. The percentage polarisation was calculated from the formula,

$$P = \frac{I_R - I_L}{I_R + I_L} \times 100.$$

3. RESULTS

(*a*) *Intensity.*—Observations were made only on cloudless clear skies. Only one narrow-band filter was used on any particular morning or evening. Meter readings were noted at regular intervals of half a minute except during late twilight when the rate of change of intensity was very small. Frequent check was made on the zero reading and photomultiplier voltage. After applying linearity and zero shift corrections, the corrected meter readings were multiplied by appropriate scaling factors so that the final values were proportional to the intensity of the light falling on the photocathode.

The readings taken on different *clear* days with the same filter were found to agree well when the photomultiplier voltage was kept very steady.

The actual readings for the same solar depression were found to differ in certain ranges on some days. This might have been due to small changes in photomultiplier voltage, changes in the scattering and absorption of light by dust and haze in the atmosphere and changes in the emission of the air-

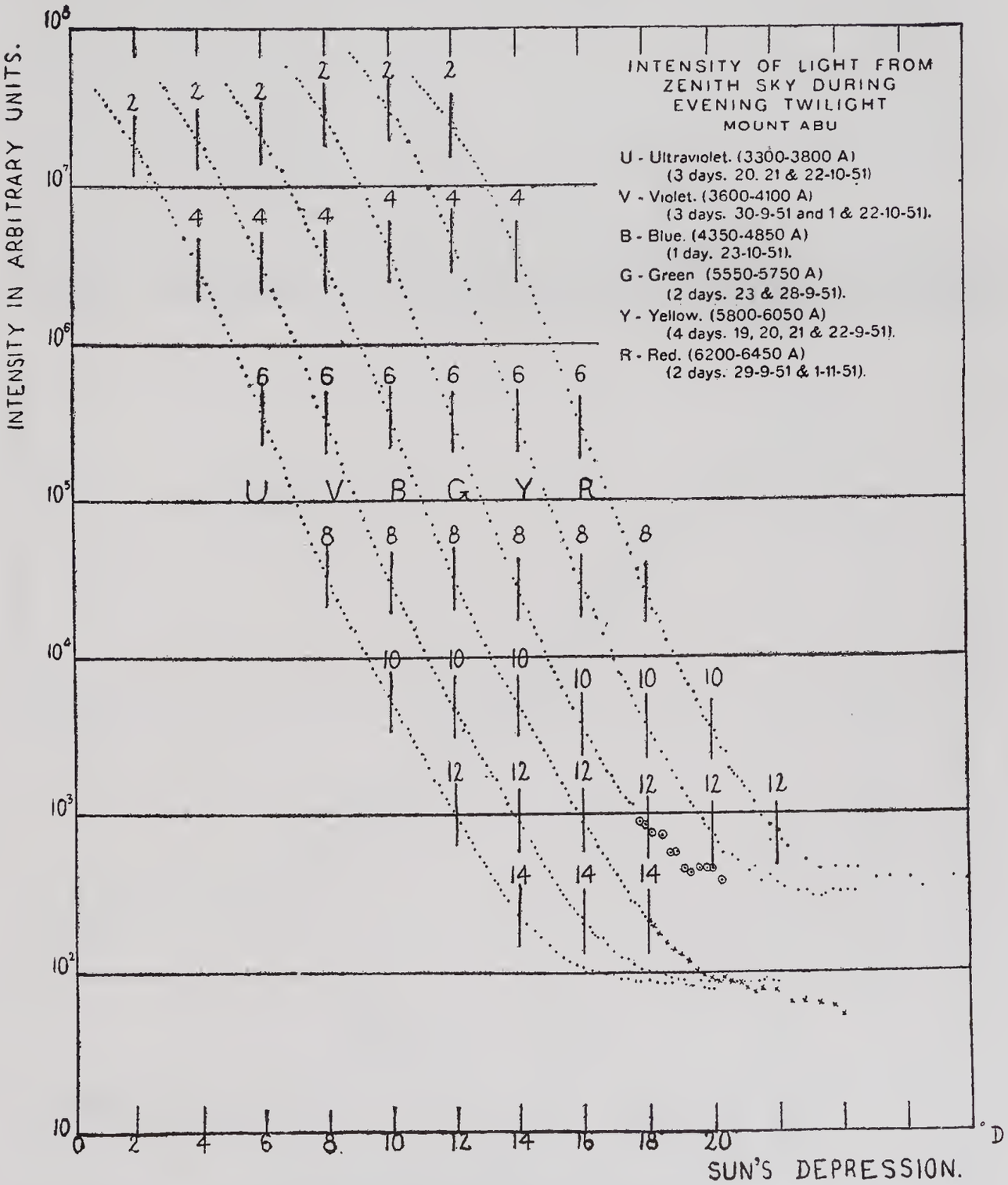
INTENSITY OF LIGHT FROM ZENITH SKY DURING EVENING TWILIGHT
MOUNT ABU
U - Ultraviolet. (3300-3800 A) (3 days. 20. 21 & 22-10-51)
V - Violet. (3600-4100 A) (3 days. 30-9-51 and 1 & 22-10-51).
B - Blue. (4350-4850 A) (1 day. 23-10-51).
G - Green (5550-5750 A) (2 days. 23 & 28-9-51).
Y - Yellow. (5800-6050 A) (4 days. 19, 20, 21 & 22-9-51).
R - Red. (6200-6450 A) (2 days. 29-9-51 & 1-11-51).
INTENSITY IN ARBITRARY UNITS.
SUN'S DEPRESSION.
U V B G Y R

FIG. 1. Intensity of the light from the zenith sky in evening twilight in defined regions of the spectrum.

glow lines. For comparing the course of the variation on different days and in different wave-lengths, the readings were reduced to a common standard by multiplying the values on a particular morning or evening by a factor which would make the readings on all the occasions have the same value at a solar depression of 5°. The means of the intensities observed on different days with the same filter and for the same solar depressions, were calculated.

The average values of the observed intensities of the zenith sky in arbitrary units during evening twilight in different portions of the spectrum are plotted against solar depression in Fig. 1. The intensity scale is logarithmic. The following are the main features of zenith sky brightness during twilight:

(1) The curves for the different wave-lengths from the near ultraviolet to red are *generally* similar from D = 0 to D = 12°, but in the shorter wave-lengths, the rate of decrease of intensity with increasing solar depression becomes markedly less when D is about 8°.

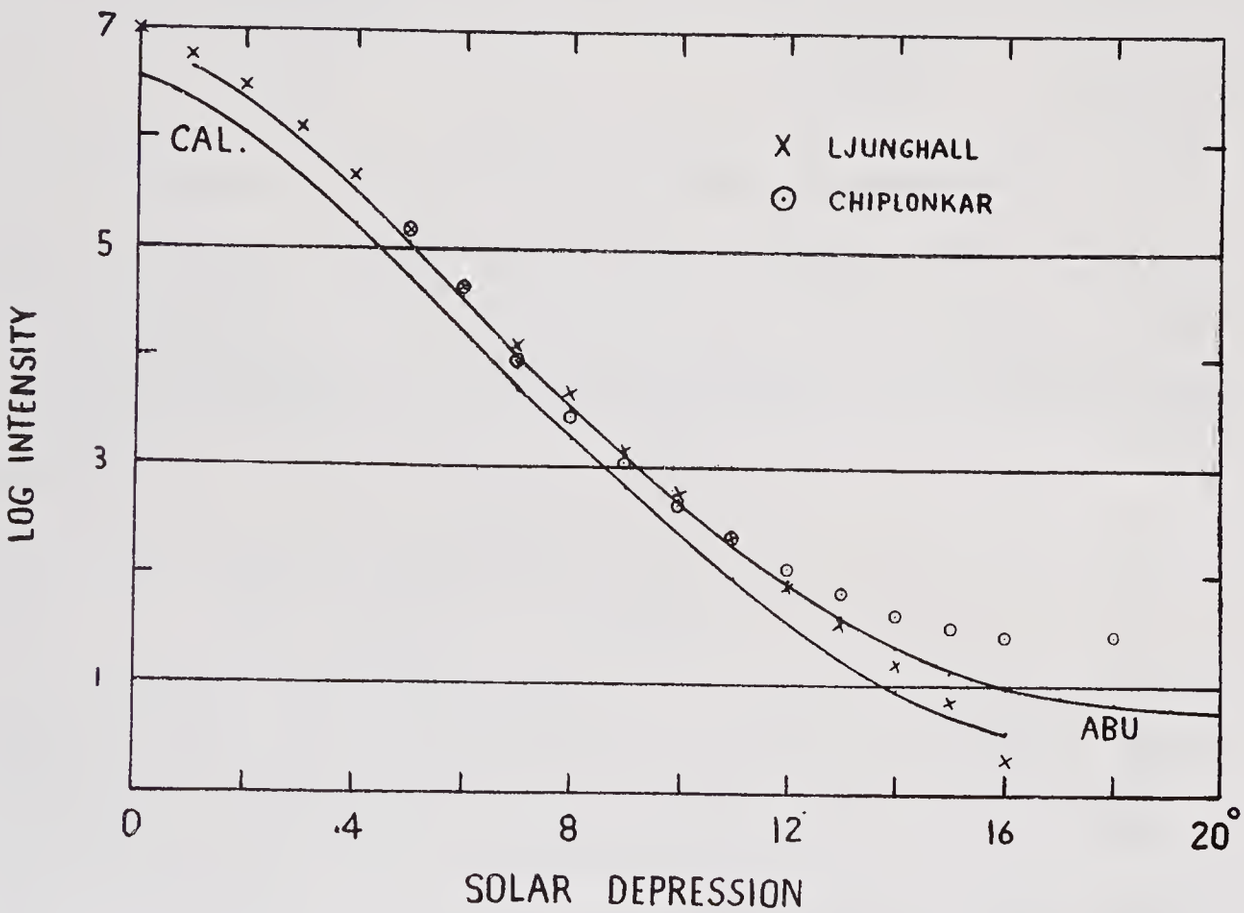

FIG. 2. Comparison of twilight zenith sky intensities as measured in different places.
ABU 4600 A.
CAL. 4400 A. Ashburn (Cactus Peak, California).
× Composite. Ljunghall (Helwan and other places).
⊙ Visual including green. Chiplonkar and Ranade (Sinhagad, Poona).

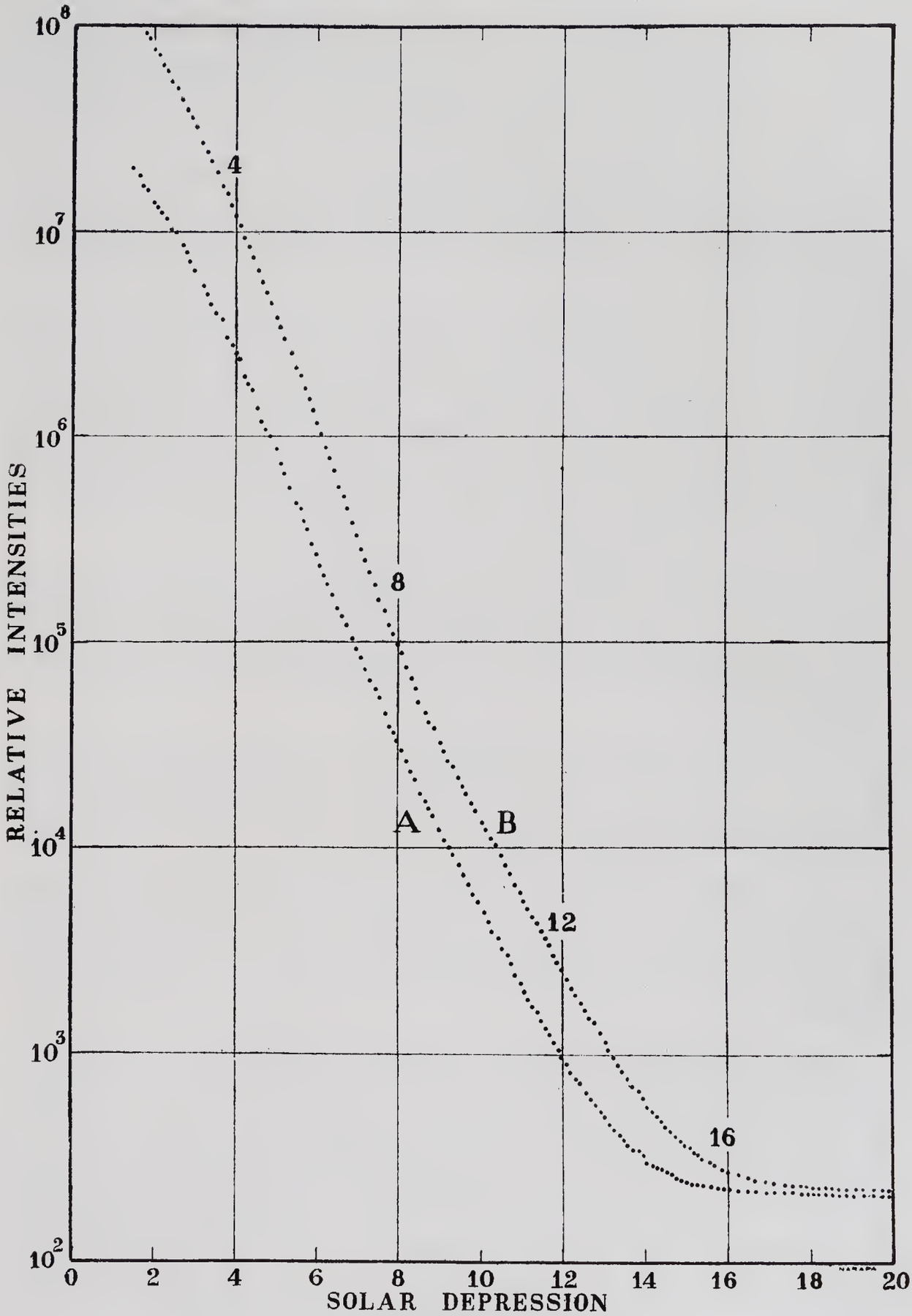

FIG. 3. Intensity of parallel and perpendicular components of zenith sky light during morning twilight (4000–5700 A).

A. Parallel component. B. Perpendicular component.

(2) While the intensities of the ultraviolet, violet and blue flatten out when the sun's depression is 16° to 18°, the intensities of the green, yellow and red which include bright lines in the night airglow flatten out when D is 13° to 14° at a higher level of relative intensity.

(3) In the green and the red, there were observed on many days a reduction in the rate of fall of intensity when D was about 12° suggesting a temporary brightening near the boundary of earth's shadow. This requires further examination.

For comparison, the values of zenith sky intensities observed during twilight by other observers are plotted side by side with the Abu values. Ashburn's measurements[1] in California were made with a phototube and filters and come closest to Abu values. The observations of Chiplonkar and Ranade[2] were made at Sinhagad near Poona with a visual photometer including the oxygen green line. Ljunghall's[3] curve is composite being made up of his own observations at Helwan with a photocell and filter and of the old visual observations of Dufay and others.

(*b*) *Polarisation.*—Observations of I_L and I_R for studying the polarisation of the sky were taken on a number of mornings and evenings: (1) with the polaroid alone (which transmits the violet, the blue and the green including an appreciable fraction of the green line 5577 A) and (2) with polaroid and blue filter.

In Fig. 3 are plotted the values of I_L and I_R for different solar depressions during morning twilight with polaroid alone. The corresponding curves for evening twilight taken with polaroid and blue filter for the spectral region 4350–4850 A, are essentially similar.

The values of the percentage polarisation as calculated from the values of I_L and I_R are plotted in Fig. 4. Curves B and C represent the values obtained in the effective spectral region 4350–4850 A for evening and morning twilight respectively, while the curves D and E are for the spectral region 4000–5700 A.

The curves showing zenith sky polarisation against solar depression are in general agreement with those obtained by Robley[4] visually at Pic du Midi. His observations extended to 16° and are also shown in Fig. 4, curve A. From Fig. 4, the following points are clear. When observations were taken with a blue filter, the zenith sky polarisation remained more or less steady at about 70% till D was 5°, and then showed a pronounced fall till D was $8\frac{1}{2}°$. Between $8\frac{1}{2}°$ and 12° solar depression, the polarisation again showed a plateau at 45% to 50%, after which it declined rapidly so that when D was greater than 18°, the zenith sky was practically unpolarised.

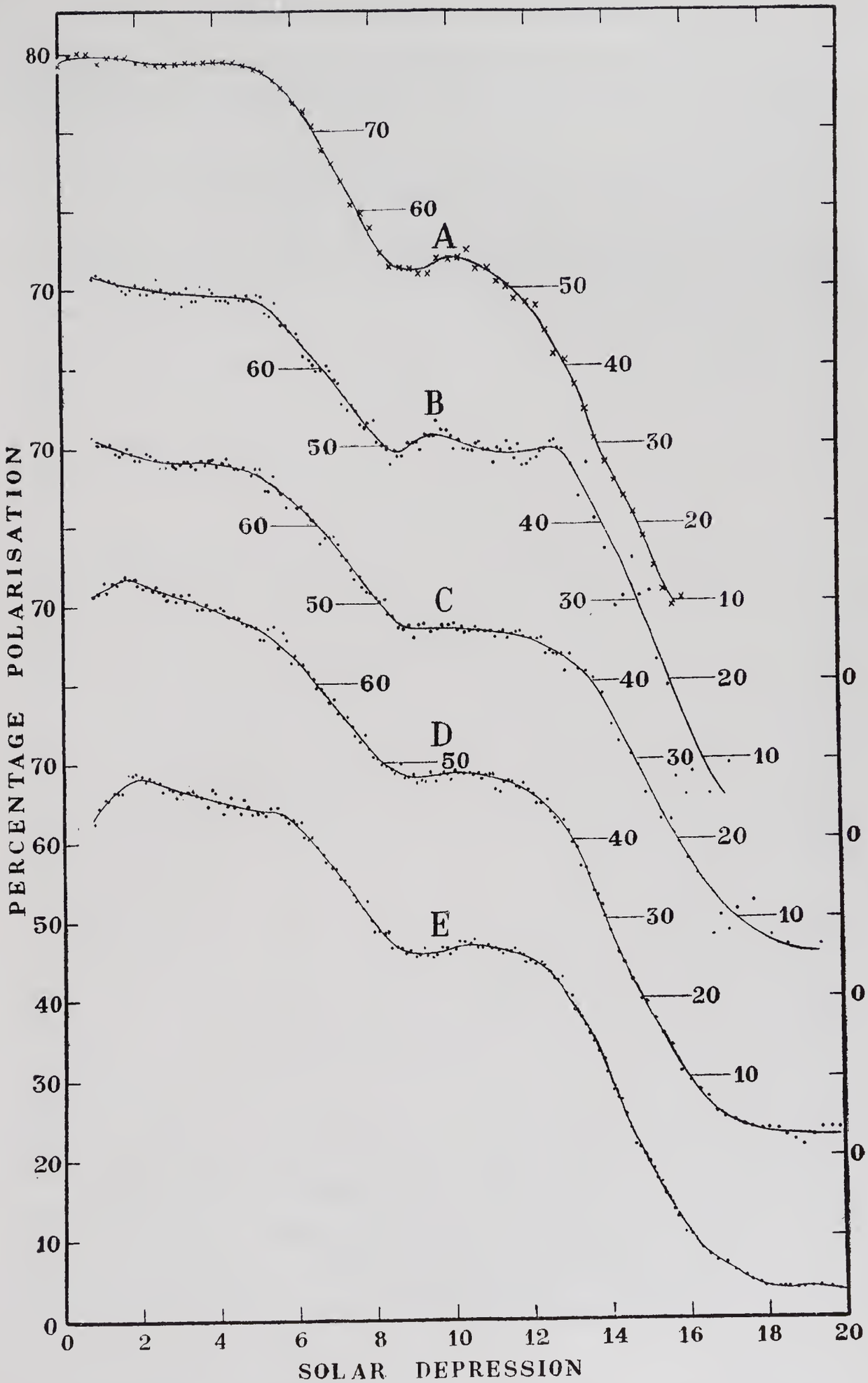

FIG. 4. Percentage polarisation of the light from the zenith sky during twilight.
A. Robley, Visual. Pic du Midi (1950) B. 4350–4850 Evening. Mt. Abu.
C. 4350–4850 Morning. Mt. Abu. D. 4000–5700 Evening. Mt. Abu.
E. 4000–5700 Morning. Mt. Abu.

Robley's curve shows similar variations, but the initial polarisation at low values of solar depression is higher, due no doubt to the clearer skies over Pic du Midi.

The curves obtained with the polaroid alone without the blue filter show similar features but the changes of polarisation are less sharp.

The polarisations at points 30° from the zenith in the vertical plane through the sun were measured both towards the sun and away from the sun

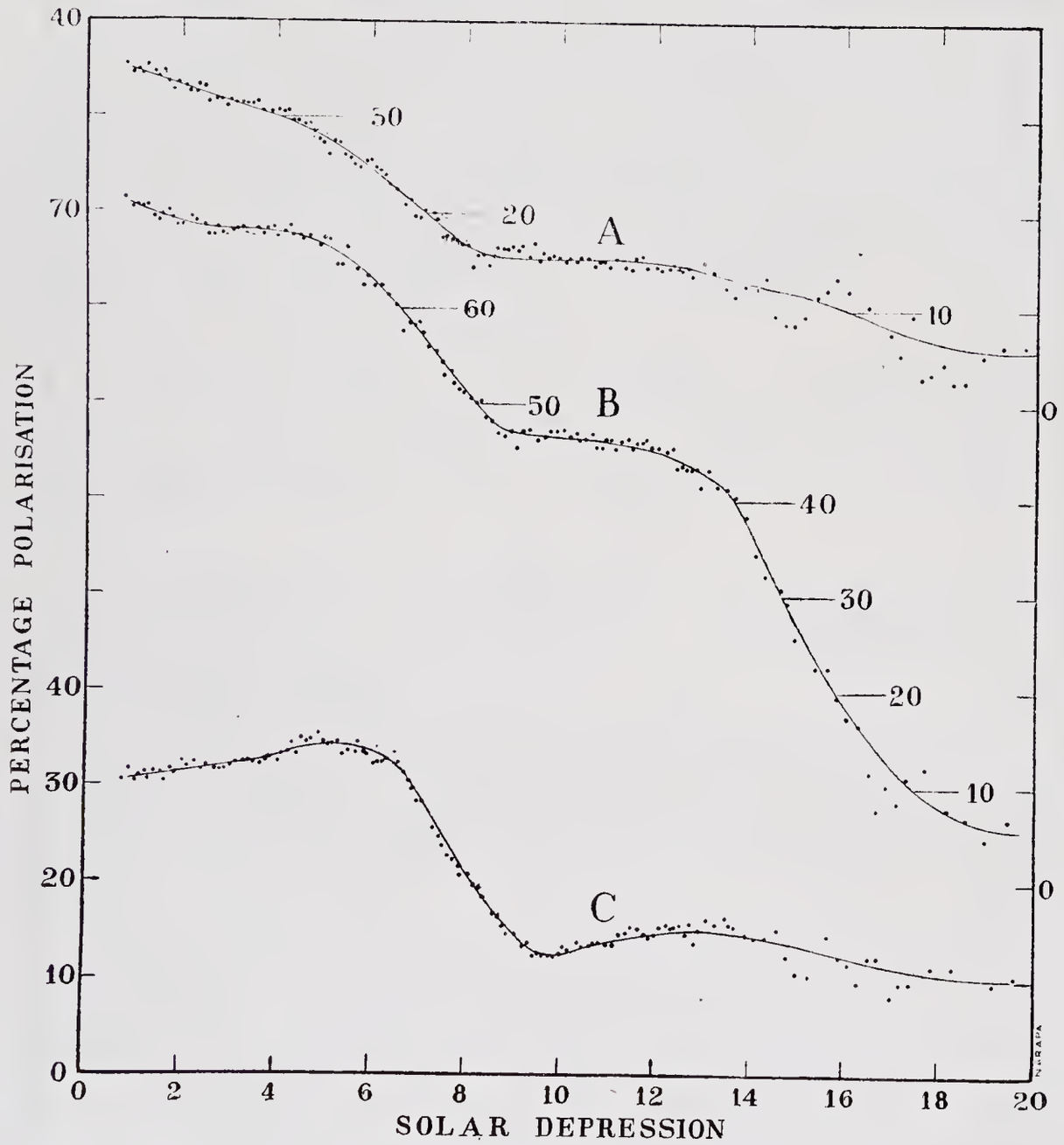

FIG. 5. Percentage polarisation of skylight in morning twilight (4350–4850).
A. 30° from the zenith away from the sun.
B. At zenith.
C. 30° from the zenith towards the sun,

on different days during morning twilight. The values of the polarisation calculated from the observed values of I_I and I_R are plotted in Fig. 5. Curves B, A and C represent the variations of polarisation with solar depression at zenith, 30° from the zenith towards the sun and at 30° from the zenith on the anti-sunside respectively.

It will be observed that the changes in sky polarisation 30° away from the zenith but towards the sun are sharper than those at the same angular distance from the zenith on the anti-sunside. The corresponding changes occur as may be expected, first on the anti-sunside, then at the zenith, and lastly on the sunside; the flattening out of the polarisation curve occurs at 9·5° on the sunside, at 9° at the zenith and at 8·5° on the anti-sunside.

To explain the humps in the polarisation curves requires further analysis of secondary scattered light.

4. Discussion

When the sun is a few degrees below the horizon, the upper part of the atmosphere is directly illuminated by the sun's rays, while the lower part lies in the shadow of the earth. The shadow region is however illuminated by scattered radiation from the sky all round, particularly from the hemisphere towards the sun. The light from the zenith sky is therefore made up of the primary scattered light from the upper part of the atmosphere and secondary (and multiple) scattered light. Owing to the greater air density in the lower part of the atmosphere, however, the main secondary scattered light would come from layers lower down in the atmosphere than the primary scattered light. As a consequence, as the sun goes down, the primary scattered light would decrease at a much faster rate than the secondary scattered light.

The observed variation of the brightness of the zenith sky with the depression D of the sun below the horizon agrees with the view that the sky illumination during twilight is only in part due to primary scattered light P. If it were due mainly to P, the variation of the sky brightness with D would be similar to the variation of the amount of air above the lower boundary of the directly illuminated upper atmosphere, that is, of the pressure at the shadow boundary. In Fig. 6 are drawn the curves of brightness RR and BB, of the zenith sky observed at Abu in the red (6300 A) and the blue (4600 A) and also the curve of pressure PP at the shadow limit. The height of the earth's shadow above the ground (for 4500 A) corresponding to different values of D are taken from Ljunghall's paper. Ljunghall assumes that above 6 km., the attenuation of light in the atmosphere is due only to molecular scattering while at lower levels, the coefficient increases, becoming at ground

level 2–2·5 times the value for molecular scattering. The refraction due to the atmosphere has been neglected. It will be seen from Fig. 6 that while the curves of BB and RR follow approximately the curve of PP down to a

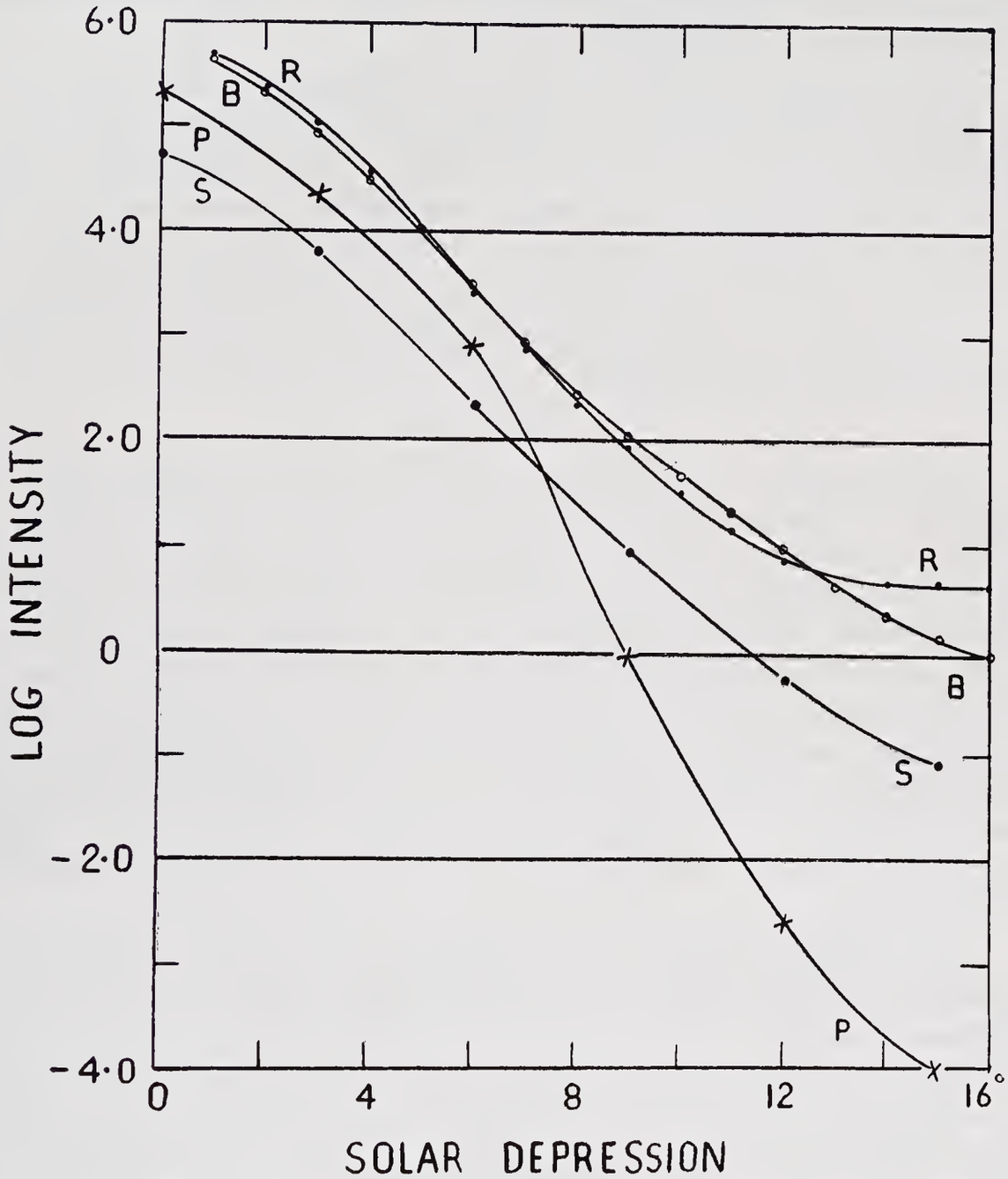

FIG. 6. Comparison of the observed zenith sky intensity with pressure at the base of the illuminated layer.

RR Observed intensity at 6300 A.
BB Observed intensity at 4600 A.
PP Pressure at the base of illuminated layer.
Height of base as given by Ljunghall.
SS Integrated illumination at ground level due to scattered light from the whole sky during twilight.

solar depression of about 6°, they deviate more and more from it at greater values of D.

At solar depressions of 12° and 15°, the values of BB are more than a thousand times greater. Many years ago, it was suggested by Hulburt[5] that secondary scattering plays an important part in twilight illumination. He showed that when the solar depression exceeds 8°, the light scattered from the zenith sky from the lower part of the atmosphere lying within the shadow of the earth but illuminated secondarily by the twilight glow is comparable in amount to the light scattered by the upper part of the atmosphere directly lit by the sun's rays. We now find that the discrepancy is enormous; can all this be explained by multiple scattering? From observations now available, it is possible to make an estimate of the relative contributions of primary and multiply scattered light to the brightness of the zenith sky during twilight.

Koomen[6] and others have given values of sky brightness measured in different azimuths and altitudes at Sacramento Peak in New Mexico (2800 m. above sea-level) for different values of sun's depression down to 15° below horizon. From these measurements, one can by numerical integration estimate the illumination due to scattered light from the whole sky at the point of observation on the earth's surface. This has been done and the following are the results.

Sun's depression below horizon	Illumination due to skylight at ground
0°	180 candles/ft.^{2}
3°	22·6
6°	0·76
9°	0·031
12°	0·0017
15°	0·00027

The values in column 2 are plotted in Fig. 6 as curve SS.

We may assume as a *first approximation* that the scattered light incident after sunset or before sunrise on a vertical column of the atmosphere above the observer will vary similarly to the integrated illumination at ground as

given in column 2 above. PP and SS will then represent respectively the relative variations of primary and secondary scattered light from the atmosphere during twilight. It is known that when the sun is on the horizon, *i.e.*, at D = 0, the secondary scattered light from the zenith for 4500 A is nearly 0·25 of the primary scattered light, but we do not know how this ratio will change when D increases. In what proportions the primary and secondary should be combined at different times after sunset is a matter for investigation.

5. Polarisation of Light from Zenith Sky during Twilight

The view that secondary scattering is the main factor responsible for extending the twilight period is borne out by the measurements of polarisation of the sky during twilight. Robley first showed from his observations at Pic du Midi that the polarisation of the clear zenith sky during twilight fell rapidly when D increased to more than 6° but that it later attained a steady value of 50% to 55% when the sun's depression was between 9° and 12°. These observations have been corroborated by our Abu observations (Fig. 4). When the secondary scattering also becomes insignificant, the light from the zenith sky is only scattered starlight and light from the airglow and is practically unpolarised. This happens when D is 16° to 18° for blue light. Robley found that with red light for which the secondary scattering would be much smaller, the first dip in polarisation and the plateau between D = 9° and D = 12° were inconspicuous. It may be observed that the sky illumination during evening twilight, especially in its later half, is markedly anisotropic, the light coming from the direction of the sun being much greater than from other directions. This light, when secondarily scattered downward by the atmosphere above the observer, will naturally have a large polarisation.

Quantitative checking of these ideas with observation requires the calculation of the intensity and polarisation of secondary scattered light by the spherical atmosphere when the sun is below the horizon. The calculations have been made and will be the subject of communication of Part II.

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B. METEOROLOGY

XI. Thunderstorms in Trivandrum.

By K. R. Ramanathan, M.A., Director of the Trivandrum Observatory.

I.—Introduction and Summary.

Thunderstorms are a regular feature of Trivandrum weather. They present well-marked seasonal and diurnal variations. The maximum activity occurs during the months March to May and in October. In the following paper, an analysis is made of the seasonal variations of thunderstorms in Trivandrum and they are discussed together with the variations of other meteorological elements, humidity, temperature and air movement both at Trivandrum and at Augustia (6,200 ft. above sea level) in the light of Simpson's theory of thunderstorm formation. According to Simpson, whenever there are strong humid, ascending air currents in the atmosphere accompanied by condensation of moisture, splitting of water-drops and separation of electricity occur. The conditions that have been recognized as essential for the formation of strong humid ascending air currents are (1) sufficient moisture in the atmosphere and (2) a vertical temperature-gradient exceeding the adiabatic lapse-rate. So far as these two factors go, they are satisfied at Trivandrum at all the months of the year. The reason why, then, thunderstorms do not occur at all seasons is shown to be connected with the existence of strong horizontal winds at and above the level of the Western Ghats in the months June to September and November to February, and the comparative absence of such steady air movements during the rest of the year. Strong horizontal winds prevent the formation of strong ascending currents.

II.—Statistics of Thunderstorms.

Observations of thunderstorms in Trivandrum made during the years 1856–1864 by Mr. J. A. Broun have been discussed in

Proc. Ind. Assn. Cult. Sci. 7, 107–114, 1921–22.

the Indian Met. Memoirs Vol. X, part 1 by Sir J. Eliot. Further records have been kept in the Trivandrum observatory from 1892 onward, when they were begun by Dr. A. C. Mitchell.

Table I gives the number of days on which thunder was heard in the different months of the years 1902–1914.

Table II gives the number of days on which lightning was seen with or without thunder.

TABLE I. *Number of days on which thunder was heard.*

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL.
1902	3	1	13	28	23	10	0	0	6	16	14	8	122
1903	2	2	6	26	17	10	0	0	2	11	8	7	91
1904	2	2	9	19	13	8	4	0	0	22	9	1	89
1905	0	4	4	23	15	2	0	0	2	10	9	0	69
1906	0	5	7	14	19	3	0	3	1	20	13	8	90
1907	2	1	17	22	21	5	2	1	14	19	12	7	113
1908	7	8	14	17	12	6	1	0	1	8	7	2	83
1909	1	7	14	22	11	1	1	2	0	14	14	7	94
1910	1	6	13	18	12	5	4	3	1	11	15	0	89
1911	0	1	12	6	17	5	1	0	3	15	8	10	78
1912	1	4	7	24	22	6	0	0	3	14	10	0	101
1913	3	4	5	20	21	4	1	2	2	10	10	6	88
1914	2	3	13	19	16	8	1	2	5	14	11	7	101
Average	2	3	10	20	17	6	1	1	3	15	11	5	93

TABLE II. *Number of days on which lightning was seen with or without thunder.*

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL.
1902	3	2	16	29	30	14	0	2	8	22	18	11	155
1903	2	4	10	30	22	12	0	0	2	15	15	9	121
1904	2	6	14	22	22	9	4	1	2	22	9	4	117
1905	0	10	13	26	26	2	0	0	5	11	16	4	113
1906	7	3	12	15	20	5	0	7	4	22	13	10	118
1907	2	7	26	25	25	8	5	1	5	24	15	7	150
1908	9	11	17	20	15	6	2	0	4	10	7	3	104
1909	1	10	16	23	18	3	1	2	0	18	19	8	119
1910	1	6	14	19	14	11	5	3	1	14	17	0	105
1911	2	2	16	10	19	8	1	1	6	15	16	12	108
1912	2	7	10	28	28	19	1	3	10	15	16	3	142
1913	4	6	6	24	25	8	1	2	8	14	17	7	122
1914	3	4	18	22	18	9	1	2	10	21	16	9	133
Average	3	6	14	23	22	9	2	2	5	17	15	7	124

It will be observed that the maximum thunderstorm activity occurs during March to May. There is also a secondary maximum in October. The distribution of thundery weather during the year is shown graphically in Figure 1.

An examination of the records also shows that the thunderstorms begin either to the north or east of Trivandrum, except just previous to the burst of the monsoon or when depressions are

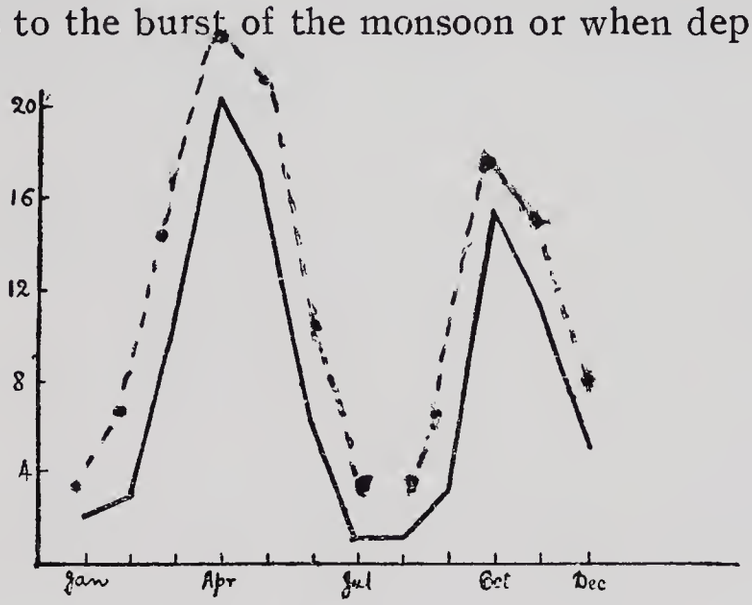

FIG. 1.

travelling close to Trivandrum (when they may begin in any direction) and that they are most active during the afternoon hours 2 to 5 p.m.

III.—Mode of Formation.

The most satisfactory theory of thunderstorm formation is that due to Dr. G. C. Simpson.[1] He showed that splashing of water drops by air currents produces electrification, positive on the drops and negative in the air. When there is opportunity for a large breaking up of water drops, a large quantity of electrification is produced. In the region of humid ascending atmospheric currents, there would be condensation of moisture due to adiabatic cooling, and if the ascending currents are strong, the condensed drops would not be allowed to fall down but would be carried up until they reach a certain size and thereafter their shape would get so much out of the spherical that they would become unstable and break up into smaller drops. Dr. Lenard has shown that the limiting size of waterdrops beyond which they cannot grow without breaking up is about 5 millimetres in diameter and the limiting velocity which drops of this size would acquire on free fall is nearly equal to 8 metres per second. Hence, no drops could fall through an ascending current of air with a vertical velocity greater

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[1] Phil. Trans. Roy. Society, 209, p. 379, 1909.

than 8 metres per second. The drops would be carried up, reach a certain size, break up, and again be carried up, grow, and break up. Dr. Simpson showed that enough electricity could be produced on the drops by such splashing as would be sufficient to account for the electricity carried down by rain.

Accepting this theory, we shall see how the conditions are favourable for the formation of thunderstorms in the months of March, April and May and in October and November, and how they are unfavourable during the other months.

The conditions favouring strong ascending currents accompanied by large condensation are:—

1. Enough moisture in the lower air for clouds to form as a result of upward movement;

2. A rate of fall of temperature with height approaching or exceeding the adiabatic lapse rate for saturated air; and

3. Absence of strong horizontal winds for a few kilometres above the earth's surface.

I. We shall take these points one by one.

Table III gives the actual pressure of the vapour present in the atmosphere in the different months of the year at Trivandrum and at Augustia peak (Lat. 8° 37′ N., Long. 77° 30′ E., height 6,200 ft. above sea level and distant 22 miles from Trivandrum, a high solitary peak in the Western Ghats where an Observatory was maintained by the Government of Travancore during the years 1856–1858 and in 1864 under the direction of Mr. J. A. Broun for taking magnetic and meteorological observations).

They are taken from the Indian Met. Memoirs Vol. X, parts I and II and are based on 24 hourly observations of the wet and dry bulb thermometer during the years 1856–1864 at Trivandrum and 1856–1858 at Augustia.

Month.	Trivandrum.		Augustia (height 6,200 ft.).	
	Mean vapour pressure in inches of mercury.	Humidity. %	Mean vapour pressure in inches of mercury.	Humidity. %
January ..	0·69	74	0·39	93
February ..	0·68	71	0·38	83
March ..	0·78	75	0·45	89
April ..	0·83	77	0·50	90
May ..	0·87	82	0·49	97

Month.	Trivandrum.		Augustia (height 6,200 ft.).	
	Mean vapour pressure in inches of mercury.	Humidity. %	Mean vapour pressure in inches of mercury.	Humidity. %
June ..	0·82	86	0·49	98
July ..	0·79	86	0·48	99
August ..	5·79	86	0·47	97
September ..	0·77	83	0·46	97
October ..	0·79	85	0·46	97
November ..	0·77	83	0·44	97
December ..	0·68	76	0·39	94

So far as moisture is concerned, there is plenty of it in all seasons of the year. Indeed, it is doubtful whether there are many other places on earth where there is so much of moisture at all seasons of the year.

II. It is not possible to get an accurate idea of the lapse rate of temperature at Trivandrum without observations with sounding balloons. We can, however, get much useful information from a consideration of the mean temperatures at Trivandrum and Augustia during the different months of the year.

Table IV, gives the mean temperatures at Trivandrum and Augustia based on 24 hourly observations ; 1856–64 at Trivandrum, and 1856–58 at Augustia.

Month.	Mean temperature at Trivandrum in °C.	Mean temperature at Augustia in °C.	Difference in °C.
January ..	24·6	12·0	12·6
February ..	25·6	13·5	12·1
March ..	26·9	15·3	11·5
April ..	27·0	16·4	10·6
May ..	26·7	15·2	11·5
June ..	25·3	14·8	10·5
July ..	24·8	14·3	10·5
August ..	24·8	14·2	10·6
September ..	25·0	14·0	11·0
October ..	25·0	14·0	11·0
November ..	25·0	13·6	11·4
December ..	24·7	12·2	12·5

The minimum difference occurs during the months of June and July and even in those months, the lapse rate is 0·36° C per 100 metres (6,200 ft.=1,890 metres) a quantity far exceeding the adiabatic lapse rate for saturated air. According to Hann, the

temperature gradient for 100 metres for saturated air at 25° C under conditions of dynamical equilibrium to a height of 2,000 metres from sea level is 0·43° C per 100 metres (Handbuch der Meteorologie, page 182). We have no data as regards temperatures higher up. So far, then, as the first two conditions for ascensional movement are concerned, they are satisfied in all parts of the year. The answer to the question why thunderstorms do not occur in all months of the year, will be clear when we have discussed the third condition.

IV.—Character of the air movement in Trivandrum.

The character of the air movement in Trivandrum is affected to a great extent by the close neighbourhood of the Western Ghats. For about 20 miles to the east of Trivandrum, the country is undulating with hills and hollows, and beyond it, rises the Western Ghats to an average height of 5,000 ft. During the months June to September, when the S.W. monsoon is in full swing, there is a strong steady wind from about N. 60° W. with little diurnal variation. During the months November to April, the air movment consists of land and sea-breezes. The N.E. winds, that obtain during this period in the south of the Peninsula to the east of the Ghats, do not penetrate into Trivandrum, sheltered as it is, by the protecting effect of the Ghats. The months May and October are months of transition.

Since the air movement at Trivandrum is largely affected by the proximity of the high Western Ghats, it is more useful to consider the air movement at a higher level where the winds would be less hampered by geographical peculiarities. For this purpose, we shall consider the air movement at Augustia. In his discussion of Augustia meteorological observations, Sir J. Eliot summarises the general character of the air movement thus :—

"The air movement at Augustia differs essentially in many respects from that prevailing at Trivandrum. The peak is the highest point of the South Travancore Hills.

In the months of December, January and February, when steady and moderate strong N.E. winds obtain in the south-west of the Bay and are continued as E.N.E. winds across the districts of Tinnevelly and Madura and when light local land and sea breezes obtain in the Travancore Coast districts and the neigh-

bouring sea area, the air movement at Augustia is determined by (and is a continuation of) the massive atmospheric current from the N.E. over the Bay which is strongest in the S.E. of the Bay and Southern India. In this season, 5% of the wind observations are of Calms, 64% of the winds are from East and 21% from N.E. and only 10% from other directions. The air movement is hence remarkably steady and is on the mean of all the data, from E.N.E., or more exactly, N. 80° E.

"Similar conditions obtain during the third period (June to Sept). The air movement at Augustia is then determined by the S.W. monsoon air current over the Arabian Sea. During this period, in the years 1856–58, about 4% of the observations were of Calms, 21% were winds from N.W. and 72% from W. and hence only 3% from the remaining six points. Winds are hence even steadier in this season than in the first season of the year. The mean wind direction is W.N.W.

"The air movement during the remaining five months of the year is essentially of a transitional character. During the second period comprising the months of March, April and May the mean winds in South Madras shift in direction from East in March and April to West in May, in which month, they are practically indentical in direction with the mean winds in June. The mean direction of the winds at Augustia during this period shift *pari passu* with the change of direction of the air movement in Southern India and the resultant is almost nil.

"The conditions in the fourth period including the months October and November are similar to those of the second period except that the transition or change is inverse to that of the second period.

"The number of Calms reported is large; 16% of the wind observations received during this period in 1856–58 were of Calms, so that they were almost as numerous as during the first transitional period March to May. It is also noteworthy that Calms are more numerous in this, as in the second season, during the day than during the night and are most frequent from 11 A.M. to 4 P.M."

Summary of weather conditions at Augustia.

December, January and February	Calms	5%
	East	64%
	N.E.	21%
	Other directions	10%
March, April and May ..	Calms	19%
	East	25%
	S.W.	33%
	Other directions	23%
June to September ..	Calms	4%
	West	72%
	N.W.	21%
	Other directions	3%
October to November ..	Calms	16%
	West	25%
	East	32%
	Other directions	27%

It will be noticed that the time of maximum thunderstorm activity coincides with the time of minimum horizontal air movement at Augustia. *Absence of strong horizontal winds in the higher layers is a* sine que non *of strong ascending currents favourable to thunderstorm development.*

During the months of March and April, when the general gradient is undefined and is too weak to exercise any control over the air movement, ascending currents begin to rise with the heat of the sun and form detached cumulus heads. These cumuli grow and with the setting in of a light humid breeze from the sea in the afternoon, they grow into large masses often crowned with false cirrus, especially to the north-east of Trivandrum where the land rise is the most marked.

By about 3 P.M. the whole sky is clouded and occasional crashes of thunder are heard. This continues for varying intervals of time and is often accompanied by rain. Ordinarily, the sky clears by about 6 P.M. and a clear night follows. As the season advances, however, the thunderstorm continues at night. The general character of the weather is very similar in October.

These considerations should apply to other places where thunderstorms are seasonal. All along the west coast of India and in Ceylon, the setting in of the monsoon is preceded by a period of thunderstorm activity.

ON TEMPERATURES OF EXPOSED RAILS AT AGRA.

NOTE PREPARED BY

K. R. RAMANATHAN, M.A., D.Sc.

(*Received 9th February, 1928.*)

Summary :—

Daily maximum and minimum temperatures of a rail laid horizontally and another fixed vertically on the ground were taken at Agra during the period May 1927 to January 1928 with a break in July and part of August. These temperatures are compared with each other and with those shown by thermometers in a standard Stevenson screen. The minimum temperatnres are also compared with "grass" minimum temperatures. Tables of mean monthly temperatures, percentage frequencies of different ranges of temperature, monthly mean diurnal ranges of temperature, morning and afternoon cloudiness and the highest and lowest temperatures observed in each month are given.

Curves of diurnal variation of rail and air temperatures based on observations made on 6th February 1927 are also given.

A metal body exposed to the sky is ordinarily colder in the morning and warmer in the afternoon than the surrounding air on account of the difference between the radiative and absorptive properties of the metal and air. The temperatures of rails exposed under Indian conditions are of interest to Engineers in connection with the construction of railways, telegraph lines and bridges. As no definite data are available on the subject, a small investigation was undertaken to find the maximum and minimum temperatures of rails exposed (1) horizontally on the ground as for railway lines and (2) vertically as for telegraph posts. Some hourly observations of temperature were taken on a few days in October 1926 and February 1927, but the main series of observations discussed in the present note are those of maximum and minimum temperatures extending over the period 13th May 1927 to 20th January 1928 with a break in July and partly in August.

The horizontal rail was 4 ft. 10 in. in length and was laid over broken stones spread out to a height of 4 inches on the open grounds of the Upper Air Observatory, Agra. A vertical hole about 1 inch deep was bored in the rail at a distance of 15 inches from one end and half filled with mercury and the bulb of the thermometer was inserted in the hole.

The vertical rail was 16 ft. in length and had a hole bored in its side at a height of 4 ft. 2 in. from the ground for receiving the bulb of the thermometer and a cork round the stem of the thermometer closed the mouth of the hole from the outside when the thermometer was in position. Suitable supports were fixed

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to the two rails to keep the thermometers in position without risk of breakage. The maximum thermometers were read at about 17 hrs. and replaced by minimum thermometers after setting. The latter were read the next morning at about 9 hrs. and replaced by maximum thermometers.

Table 1 gives the monthly means of the minimum temperatures recorded in each month in the Stevenson screen and the differences between these and the means of the minimum temperatures shown by the vertical rail, ground rail and grass minimum thermometers. The number of observations on which the several averages are based are given under *n*. The "grass" minimum thermometer was supported horizontally on two wooden forks at a height of about two inches from the earth, the ground underneath being kept free from growth of any kind including grass. The early morning cloudiness expressed in tenth parts of the sky are also given in the last column. The data are represented graphically in Fig. 1.

TABLE 1.

Monthly mean minimum temperatures.

Month.	Stevenson screen. t		Grass minimum. t_1		Ground rail. t_2		Vertical rail. t_3		Morning cloudiness in tenths of sky.
	n	t	*n*	$t-t_1$	*n*	$t-t_2$	*n*	$t-t_3$	
		°F.		F°.		°F.		°F.	
May 1927 . .	*18*	78·0	*18*	5·1	*16*	4·2	*18*	1·9	2·1
June „ . .	*30*	82·1	*23*	3·5	*30*	2·9	*30*	1·4	3·7
July „ . .	*31*	79·6	*27*	1·5	...	...	...	...	7·8
Aug. „ . .	*26*	77·3	*26*	0·6	*22*	0·9	*25*	0·8	8·6
Sept. „ . .	*28*	72·5	*29*	1·5	*25*	1·4	*27*	1·3	3·2
Oct. „ . .	*31*	64·1	*24*	2·8	*31*	2·9	*30*	1·9	2·6
Nov. „ . .	*30*	52·5	*30*	4·0	*29*	3·4	*29*	1·8	2·4
Dec. „ . .	*25*	46·9	*25*	4·2	*25*	3·4	*25*	1·8	2·8
Jan. 1928 . .	*19*	44·7	*19*	3·6	*18*	3·3	*19*	2·2	3·8

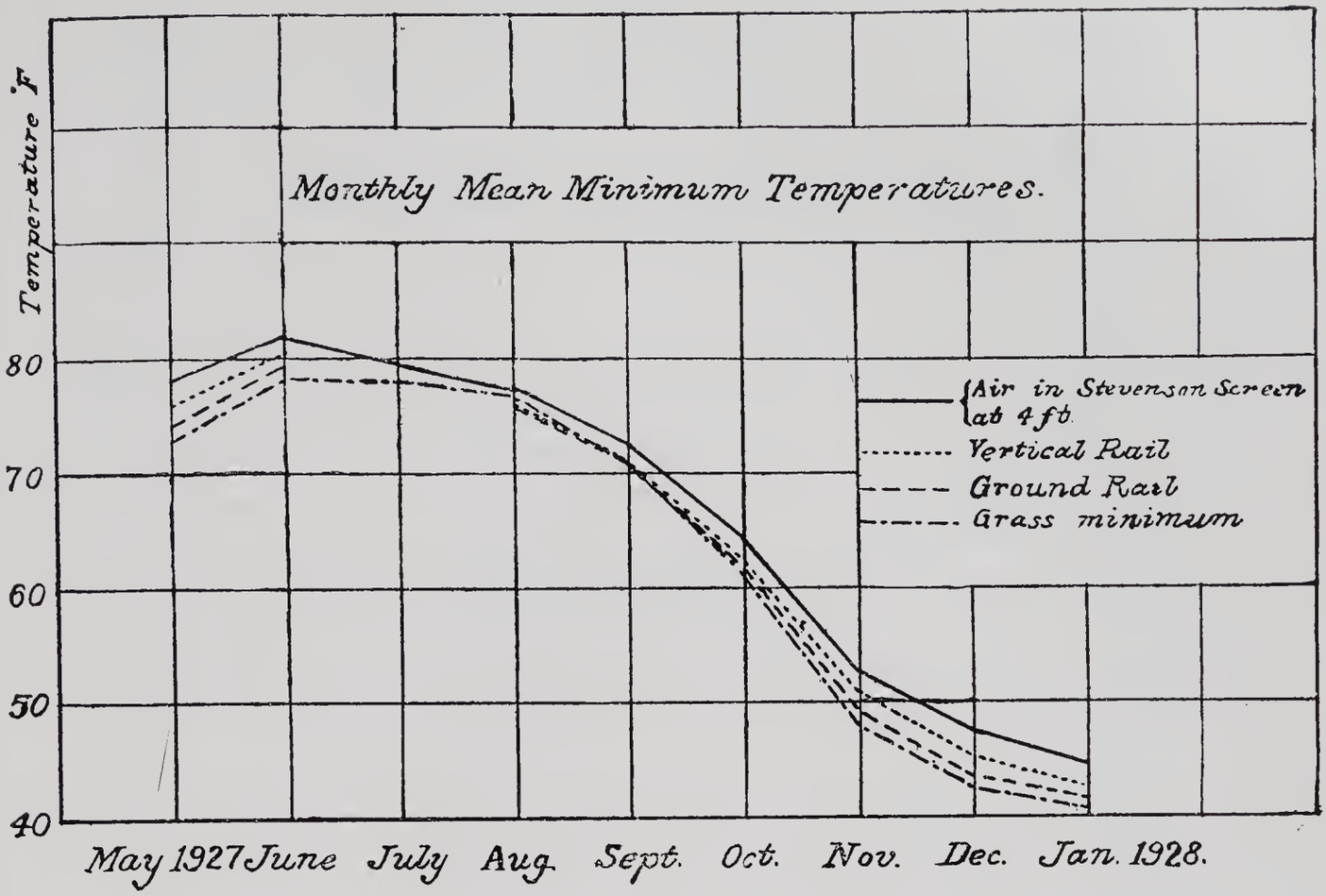


Fig 1.

It will be noticed that minimum thermometers in the different exposures give readings in the following order :—Stevenson screen highest, then vertical rail, ground rail and grass minimum. The last two, however, differ by very little ; even the largest monthly difference does not exceed 1°F. and during the wet months, the difference is practically *nil*. The vertical rail also shows the same monthly minimum temperature as the ground rail in the monsoon months, but shows higher values in other months, the largest excess 2°F. being in the dry, hot month May.

Table 2 gives the percentage frequencies of occurrence of different ranges of minimum temperature in each of the months. As the ground rail and grass minimum temperatures show very little systematic difference, only the average of the frequencies of these two are given.

The largest scatters of all the temperatures occur in June and November. The former is the month of transition between the hot and monsoon seasons and the latter when post monsoon conditions give place to those of the winter. The figures for November show two distinct maxima, one maximum corresponding to that for October and the other to that for December. This double maximum in November is not however shown in the data of every year. Examining the Stevenson screen minimum temperature data of the years 1922—26, the double maximum was evident in 1922 and 1925 but not in the other years or in the mean. There are no minimum temperatures above 85° F. in May, while there is a considerable number in June. This is due to the rapid falling off of "night radiation" consequent on the increase of moisture-content of the

TABLE 2.

Percentage frequencies of different ranges of minimum temperatures.

Ranges of temperature. °F.	May 1927.			June 1927.			July 1927.			August 1927.			September 1927.			October 1927.			November 1927.			December 1927.			January 1928.		
	t	$\frac{t_1+t_2}{2}$	t_3	t	$\frac{t_1+t_2}{2}$	t_3	t	t_1	t_3	t	$\frac{t_1+t_2}{2}$	t_3	t	$\frac{t_1+t_2}{2}$	t_3	t	$\frac{t_1+t_2}{2}$	t_3	t	$\frac{t_1+t_2}{2}$	t_3	t	$\frac{t_1+t_2}{2}$	t_3	t	$\frac{t_1+t_2}{2}$	t_3
30—34·9	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5	...
35—39·9	...	...	...		...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	17	3	...	12	4	21	27	32
40—44·9	...	...	...	...	...	...	..	...	...	...	...	...	...	...	...	...	...	...	17	24	21	24	68	52	32	51	37
45—49·9		...	.	..	...	...	...	...	...	...	...	...	...	...	...	...	..	...	33	15	27	64	12	36	37	17	26
50—54·9	..	...	...	...	...	...	...	...	...	...	...	...	...	..	...	...	8	3	7	13	14	8	8	4	11	...	5
55—59·9	...	...		...	...	...	...	...	...	.	...	...	...	4	4	16	41	33	23	23	24	4	...	4	.	...	...
60—64·9	..	4	...	...	8	...	...	...	...	...	...	...	18	43	41	45	31	33	17	7	10	...	...	...	.	...	...
65—69·9	...	19	...	3	8	7	...	...	...	...	...	...	64	35	37	35	11	27	3	...	...	...	...	...	...	...	...
70—74·9	33	47	50	13	11	13	3	8	...	12	15	16	18	19	18	3	9	3	...	...	...	...	...	...		...	...
75—79·9	33	21	28	13	27	20	55	69	...	85	85	84	...	...	...	...	...	..	...	...	...	...	...	...	...	...	...
80—84·9	33	10	22	40	27	30	35	19	...	3	...	...	...	...	...	...	...	...	...	...	...	..		...	...	...	...
85—89·9	...	...	...	20	15	23	6	4	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	..	...	...
90—94·9	...	...	...	10	4	7	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	..	...	...

t = Air in Stevenson screen. t_1 = Grass. t_2 = Ground rail. t_3 = Vertical rail.

atmosphere with the progress of monsoon conditions in the upper layer of the atmosphere over Agra. The smallest scatter occurs in August, the month of maximum humidity and cloudiness.

Table 3 gives the monthly mean maximum temperatures in the Stevenson screen and the differences between these and the mean temperatures of the ground and the vertical rails. The mean cloudiness between 12 and 16 hrs. is also given.

As might be expected, the ground-rail monthly maxima are always higher than the vertical rail maxima and the latter higher than the air maxima. The difference between the temperatures of ground-rail and of air at 4 feet depends primarily on the maximum intensity of sunlight and on the wind movement. The former is a function of the altitude of the sun at noon and the transparency of the atmosphere. It is interesting to note that the maximum monthly value of $t'_2 - t'$, 29°F., occurred in the cloudiest month August. This is because, in this month, when the sky does clear, the intensity of sunlight is high, as the average maximum altitude of the sun is about 77°, and the dust content of the atmosphere is small owing to the monsoon rains. No observations are available for July, but the difference is expected to be large in this month also.

TABLE 3.

Monthly mean maximum temperatures.

Month.	Stevenson screen. t'		Ground Rail. t'_2		Vertical Rail. t'_3		Cloudiness between 12 and 16 hrs.
	n	t'	*n*	$t'_2 - t'$	*n*	$t'_3 - t'$	
		°F.		°F.		°F.	
May 1927.	*18*	106·6	*16*	26·4	*14*	14·0	2·6
June „	*30*	105·8	*25*	24·5	*30*	12·1	3·7
July „	*28*	94·3	..	...	...	...	7·7
Aug. „	*24*	88·7	*26*	29·1	...	...	9·2
Sept. „	*30*	93·2	*30*	28·0	*29*	14·3	3·5
Oct. „	*31*	92·7	*31*	25·4	*31*	15·3	2·4
Nov. „	*30*	79·9	*29*	23·4	*29*	16·3	3·7
Dec. „	*24*	77·0	*24*	24·7	*24*	18·9	4·6
Jan. 1928	*19*	70·8	*19*	22·7	*18*	17·8	4·1

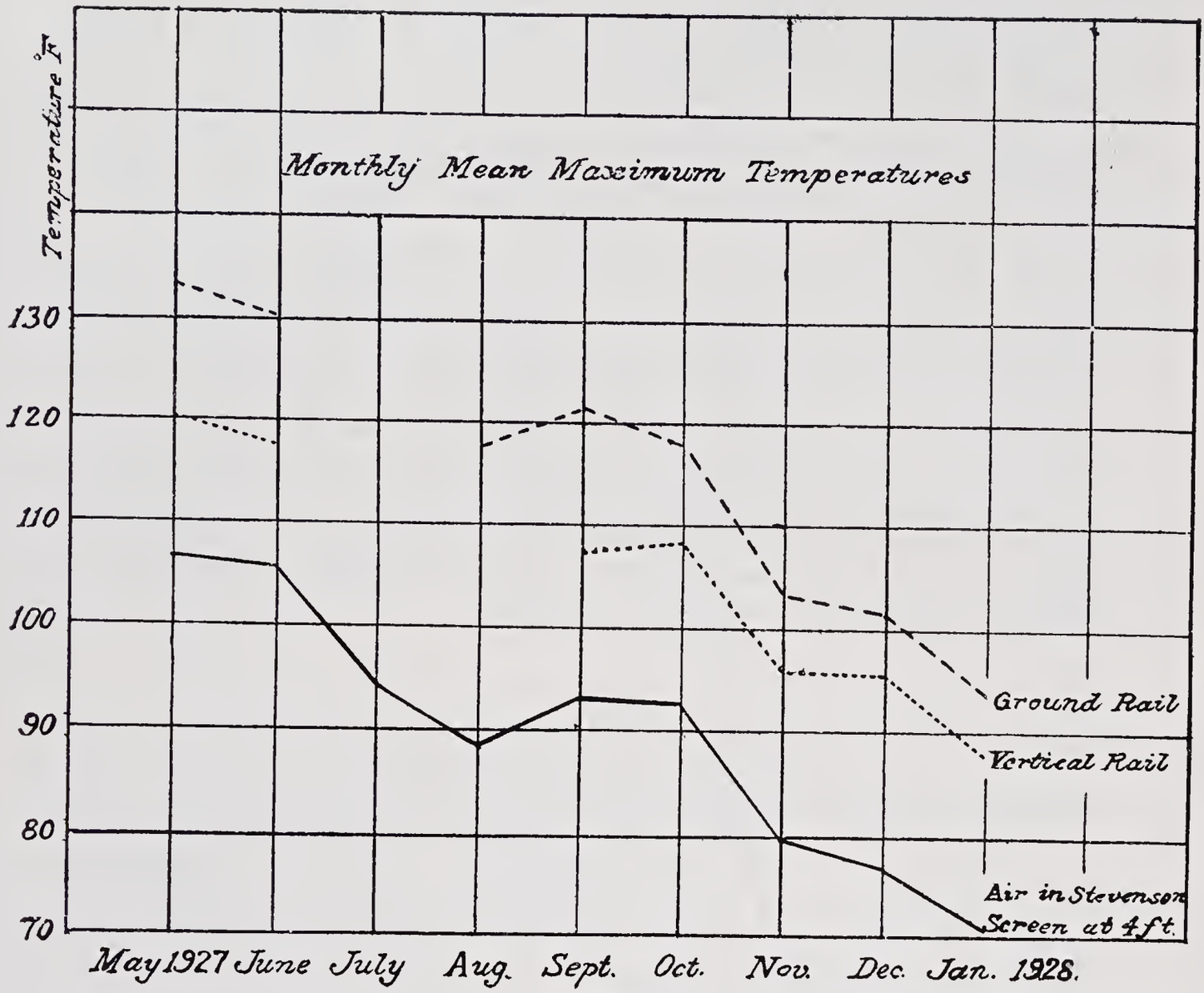


Fig. 2

Another interesting feature shown by these data is that the difference between the highest temperature attained by the horizontal and vertical rails is smaller during the months November, December and January than during the other months. The reason is fairly obvious. The maximum altitude of the sun is lowest during the winter months, the lowest value 40° occurring on December 21st (the latitude of Agra being 27° N.). At noon in the winter months, the energy received in unit time by a unit area either horizontal or vertical would be practically the same. At other hours, the vertical surface would have the advantage. On the other hand, in a month like June when the sun is nearly vertical, a horizontal surface would receive much more energy than a vertical one, and the difference of temperature between the horizontal and vertical rails would therefore be greater. The fact that one side of the horizontal rail is always in contact with the ground while the vertical rail is surrounded on all sides by moving air would always make the maximum temperature of the former higher.

Table 4 gives the percentage frequencies of occurrence of different maximum temperatures.

TABLE 4.

Percentage frequencies of occurrence of different maximum temperatures.

Range of temperature. °F	May 1927.			June 1927.			August 1927.			September 1927.			October 1927.			November 1927.			December 1927.			January 1928.		
	t′	t'_2	t'_3	t′	t'_2	t'_3	t′	t'_2	t'_3	t′	t'_2	t'_3	t′	t'_2	t'_3	t′	t'_2	t'_3	t′	t'_2	t'_3	t′	t'_2	t'_3
50—59·9	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	5	...	...
60—69·9	...	...	..	...	...	...	...	...	...	...	...	...	...	...	...	7	...	...	4	...	...	16	...	...
70—79·9	...	...	...	...	...	...	4	4	...	3	...	...	3	...	...	43	...	3	67	4	4	79	11	17
80—89·9	...	...	..	3	...	...	58	4	...	27	...	3	13	3	3	50	14	17	29	...	12	...	11	28
90—99·9	...	...	...	3	3	4	38	8	...	70	3	10	84	...	6	...	10	41	...	21	58	...	68	56
100—109·9	72	...	...	80	3	8	...	23	..	...	10	49	...	6	54	...	48	38	...	75	25	...	11	...
110—119·9	28	...	29	13	3	44	...	42	...	...	23	38	...	42	36	...	28	...	...	...	..	...	...	..
120—129·9	...	25	71	...	27	44	...	15	...	...	47	...	...	50	..	.	...	...	...	...	...	...	...	...
130—139·9	...	75	..	...	60	..	...	4	...	...	17	...	...	...	...	...	...	...	...	...	..	...	...	...
140 and above	...	...	...	...	3	...	...	..	...	..	...	...	...	...	...	...	...	...	...	...	...	...	...	...

t′ = Air in Stevenson screen. t'_2 = Ground Rail. t'_3 = Vertical Rail.

The mean monthly diurnal ranges of temperature are given in table 5.

TABLE 5.

Mean monthly diurnal ranges of temperatures.

Month.	Diurnal Range.			Cloudiness.
	Stevenson screen.	Ground Rail.	Vertical Rail.	
	°F.	°F.	°F.	
May 1927	28·6	59.2	44·5	2·3
June „	23·7	51·1	37·2	3·7
July „	14·7	...	...	7·7
Aug. „	11·4	41·4	...	8·9
Sept. „	20·7	50·1	36·3	3·3
Oct. „	28·6	56·9	45·8	2·5
Nov. „	27·4	54·2	45·4	3·1
Dec. „	30·1	58·2	50·8	3·7
Jan. 1928	26·1	52·1	46·1	3·9

The diurnal ranges and cloudiness are shown graphically in figure 3. The dependence of diurnal ranges on cloudiness is clearly marked. The ranges are least in the monsoon months at Agra, *viz.*, July and August.

Considering monthly averages, the ground rail has a higher range than the air, the excess varying from 26°F. to 31°F. while the corresponding excess for the vertical rail lies between 13°F. and 20°F.

The highest maximum and minimum temperature and also the largest range of temperature observed on any day during each month are given in table 6.

TABLE 6.

Month.	Air at 4 ft.			Ground rail.			Vertical rail.		
	Lowest min.	Highest max.	Largest range.	Lowest min.	Highest max.	Largest range.	Lowest min.	Highest max.	Largest range.
	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	°F.
May 1927	73·6	113·2	35·3	68·3	139·7	66·1	71·5	124·4	48·0
June „	69·7	111·8	41·3	63·2	142·0	78·8	66·9	127·8	58·5
July „	74·5	105·9	21·0	...	...	...	...	...	...
Aug. „	72·5	97·9	18·9	71·5	130·0	54·6	71·9	...	...
Sept. „	67·0	99·9	31·5	64·6	133·7	69·1	64·1	11 ·9	54·7
Oct. „	56·1	96·1	35·7	52·6	127·5	69·9	53·6	118·6	59·2
Nov. „	42·5	89·1	37·9	37·7	117·3	70·7	39·0	108·3	62·6
Dec. „	41·9	82·6	37·6	37·9	109·5	68·7	39·8	104·4	60·4
Jan. 1928	36·9	77·0	33·3	34·7	105·7	60·8	35·0	99·7	59·9

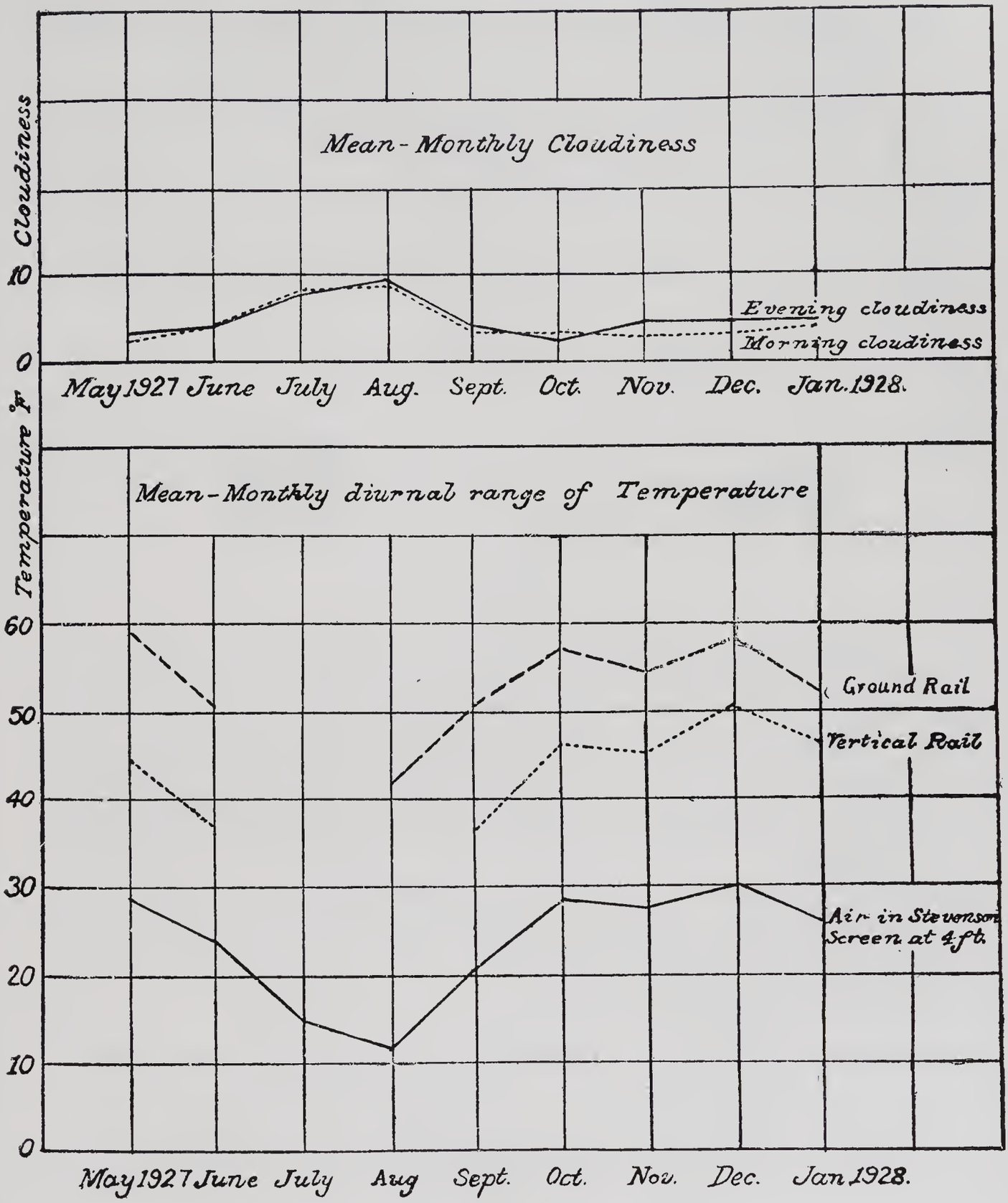


Fig. 3.

An attempt was made to find the effect of morning wind on the difference between Stevenson screen minimum and ground minimum temperatures and of afternoon wind on the difference between Stevenson screen maximum and vertical rail maximum temperatures. Wind measurements are available only at the Dines head which is at a height of about 70 ft. above ground and these winds were therefore

used. Owing to the small variance of the wind from day to day and the numbers of controlling factors involved, the effect could not be brought out clearly.

As has been indicated in the introduction, some hourly observations of the ground-rail, the surface of the ground, the vertical rail and of air in the Stevenson screen were taken on 5 days in October 1926 and in February 1927. The ground temperatures were taken by means of a "surface" thermometer* and air temperatures by means of an Assmann. The surface thermometer (fig. 4) was made by inserting the bulb of a small mercury thermometer in a properly shaped cylindrical fold in a plate of copper about 1·5 cm. square and covering the non-plane side of the plate with felt.

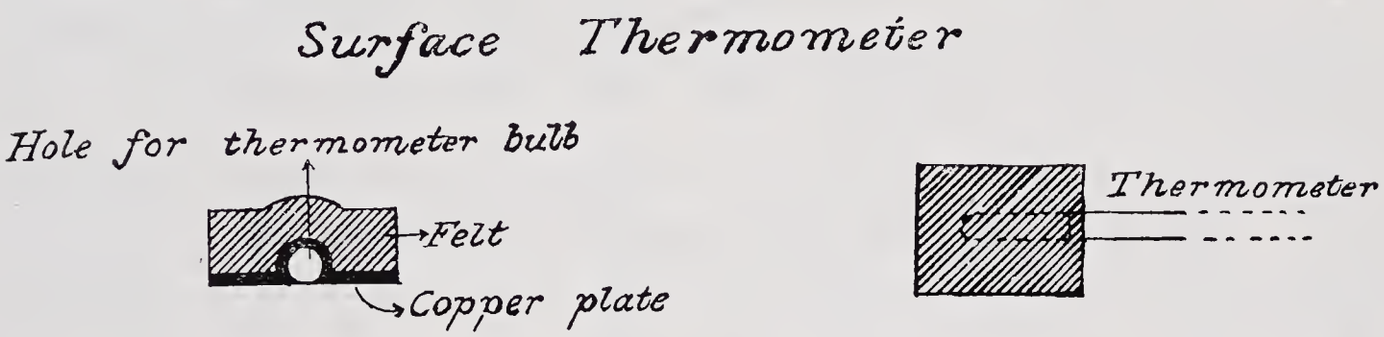


Fig. 4.

The copper plate was moved over the surface whose temperature was to be determined until the reading became constant. To show the nature of the diurnal variation of the temperatures, the values obtained on the 6th February 1927 are shown graphically in figure 5. The day was slightly clouded with cirrus and alto-cumulus clouds. The lag of the air temperature behind those of the rails and ground in the afternoon and the higher temperature of the vertical rail in the morning are noteworthy features and their general explanation does not present any difficulties.

Some observations were also taken on a few clear days to see how the temperature of the vertical rail varied with height. The rail temperatures were taken with the surface thermometer described above. The values in the following table show the nature of the results obtained.

TABLE 7.

Date and time.	Air in Stevenson screen.	Ground temperature.	Temperature of Vertical rail.					Remarks.
			Ground level.	2 ft. above ground.	4 ft. above ground.	6 ft. above ground.	10 ft. above ground.	
	°F.	°F.	°F.	°F.	°F.	°F.	°F.	
25th October 1926 at about 14 h. 45 m.	88·0	116·8	102·7	104·0	102·9	101·8	...	
5th February 1928 at about 14 h. 10 m.	68·9	78·3	79·2	82·2	80·1	80·6	79·7	Rain on previous night and soil moist.

* The surface thermometer was designed by Mr. G. Chatterji, Meteorologist.

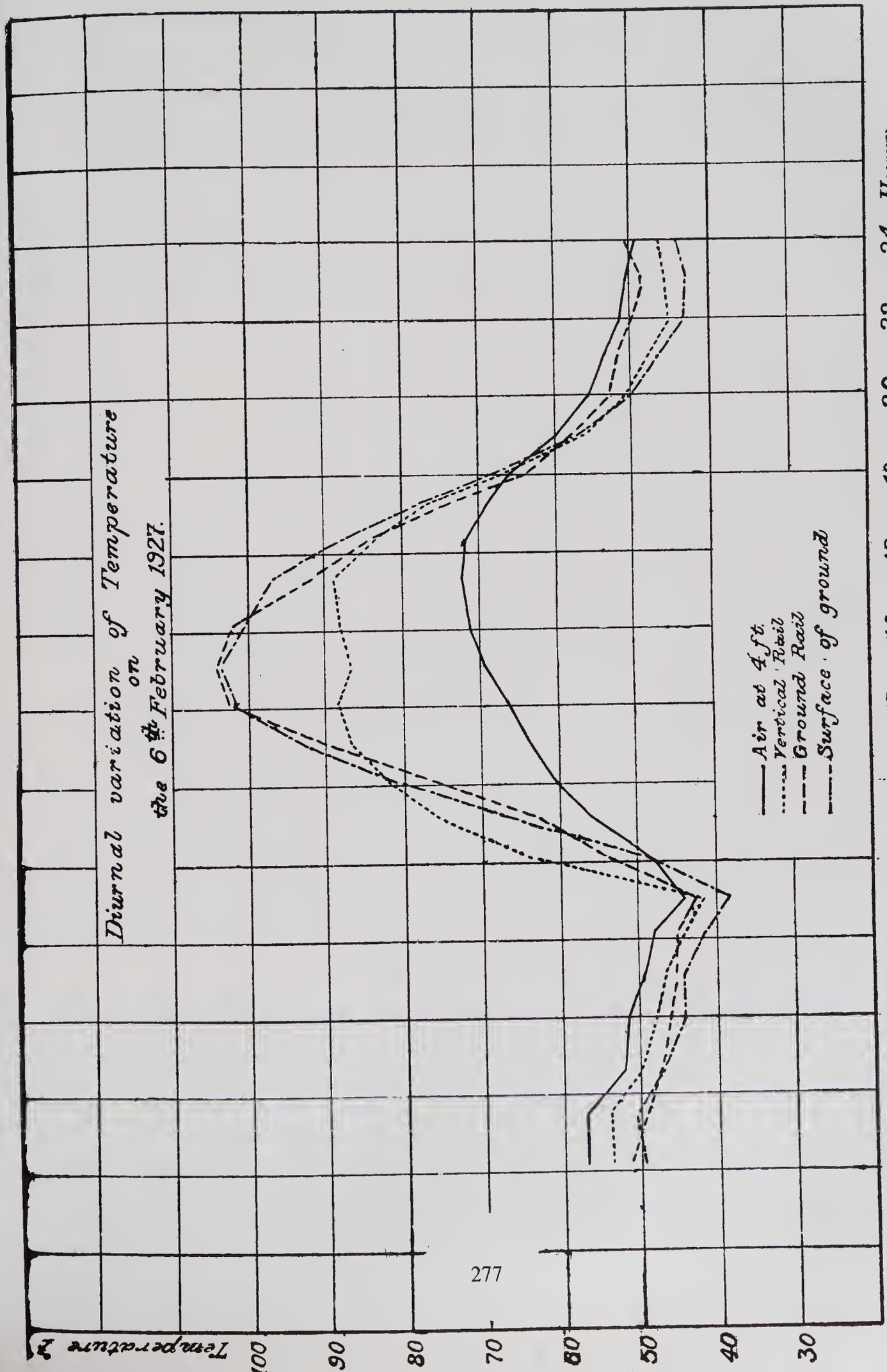

Diurnal variation of Temperature on the 6th February 1927.
Air at 4 f't.
Vertical Rail
Ground Rail
Surface of ground
Temperature F
Hours
100
90
80
70
60
50
40
30
0
2
4
6
8
10
12
14
16
18
20
22
24
277

Fig 5.

The temperature of the rail at 2 ft. above ground was higher than that at ground level on both the occasions and is no doubt due to the conduction of heat from the rail into the soil, the lower end of the rail being at a depth of about 4 ft. within the earth. The decrease of temperature above 2 ft. is mainly due to increased ventilation. It will be noticed that the temperature at 4 ft. may be taken as a fair average for the temperature of the rail even during the hottest part of the day.

MGIPC—S1—VIII-3-128—13-6-29—400.

Distribution of Temperature in the First 25 Kilometres over the Earth.

SIR NAPIER SHAW, in his "Manual of Meteorology", gives on p. 100 of vol. 2 a very interesting diagram showing the distribution of temperatures in the upper air over the globe. As pointed out by Dr. C. W. B. Normand in his review of the book in the *Quarterly Journal of the Royal Meteorological Society* (vol. 54, p. 275; 1928), the diagram does not represent exactly the peculiarities of the distribution of temperature in the stratosphere over the tropical and subtropical regions. An attempt has therefore been made to prepare a modified diagram, using all the data now available. It shows (Fig. 1) the probable distribution of isotherms in the atmosphere up to 25 km. in summer and winter over the northern hemisphere. The dotted lines are based on very few observations and are therefore mainly conjectural. The principal features of the diagram may be briefly summarised.

(1) The stratosphere is not isothermal over any particular place, but above a certain level there is a tendency for the temperature to increase with height.

(2) The coldest air over the earth, of temperature about 185° A., lies at a height of some 17 gkm. over the equator in the form of a flat ring surrounded by rings of warmer air.

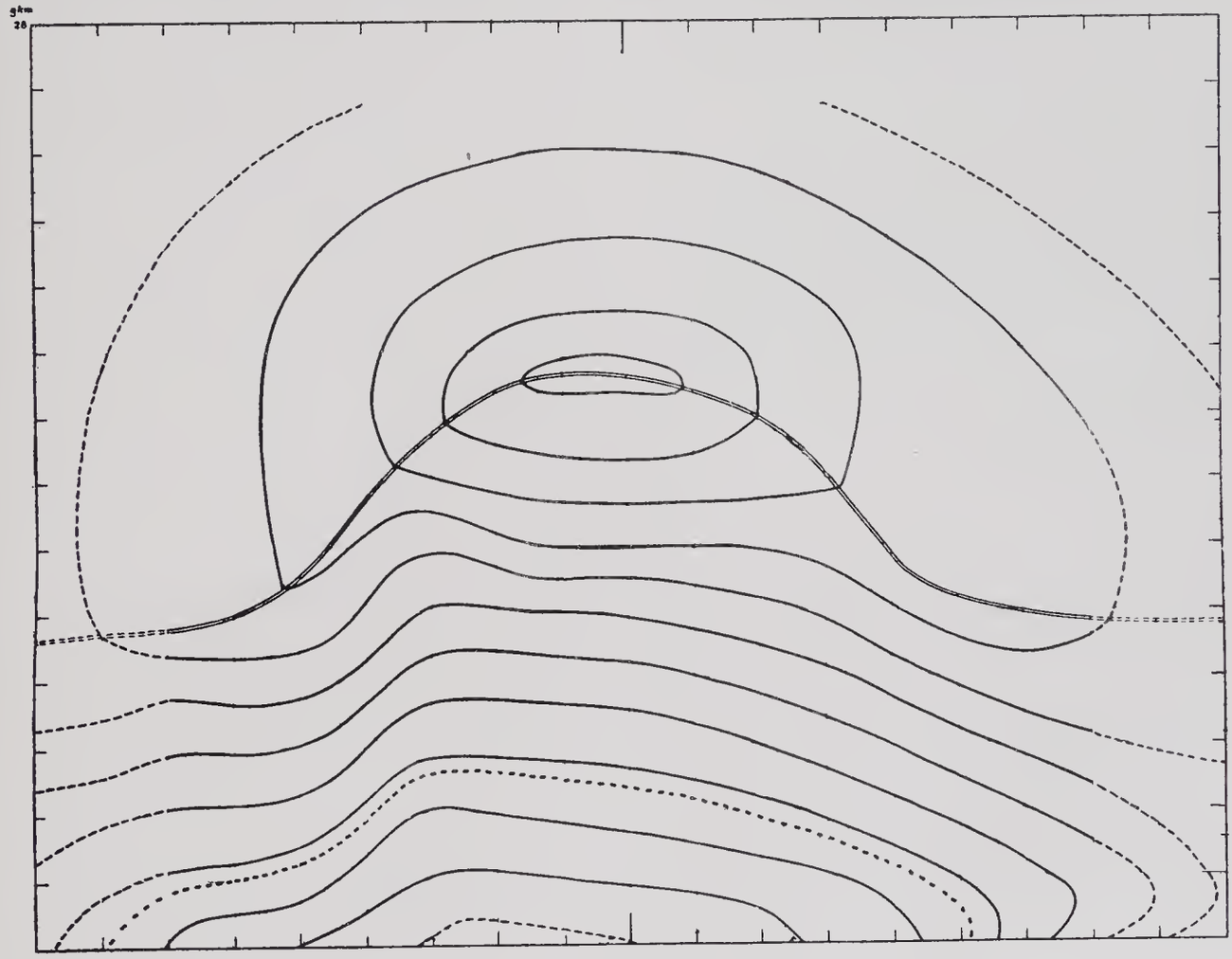
(3) The surface of the tropopause has a relatively steep slope towards the pole between latitudes 30° and 50° in summer and between 25° and 45° in winter.

(4) The ring of lowest temperature at the tropopause is displaced towards the summer hemisphere.

(5) There is a ridge of high temperature in the tropopause between latitudes 20° and 40° N. in summer corresponding to the ridge of high pressure at 8 km. over those latitudes (see Sir Napier Shaw's chart of 8 km. isobars in July, *loc. cit.* p. 262).

The evidence for (1) and (2) comes from the results of sounding balloon ascents at Batavia, Agra, and in the United States of America (Blair, *Bull. Mt. Weather Obs.*, vol. 4, part 4, pp. 183-304; 1912). The rise of temperature with height in the stratosphere over these places cannot be considered to be due to insolation, as most of the Agra ascents and many of the American ascents began late in the day when the sun was low. Bemmelen has given strong reasons for believing that the rise of temperature in the stratosphere which he observed over Batavia could not have been due to insolation. The Agra and Batavia results indicate a temperature of about 220° A. at a height of 24 km., and the American results show about 230° A. at 25 km.

The seasonal variation of temperature of the tropopause at Batavia and Agra is illustrated in Fig. 2 and shows (4) clearly. The height of the tropopause over



No. 3109, VOL. 123]

Nature, 123, 834–835, 1929.

Batavia does not show such well-marked variation as that of temperature, but the following figures taken from Bemmelen (*Proc. Roy. Acad.*, Amsterdam,

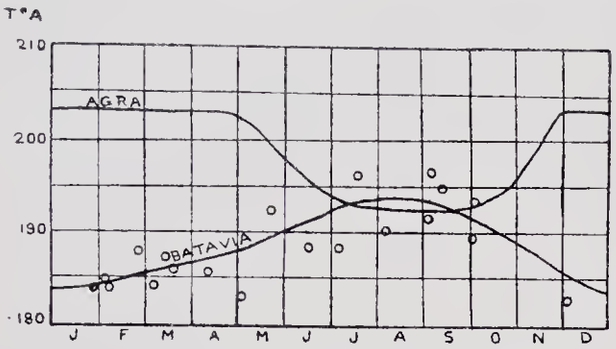


FIG. 2.—The points marked in the figure refer to Batavia temperatures.

vol. 20, p. 1313) show that the variation is similar to that which occurs over Agra but displaced by about six months.

HEIGHTS OF TROPOPAUSE OVER BATAVIA (KM.).

Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
17·8	17·6	17·3	17·0	16·5	16·2	16·0	16·5	17·0	17·4	17·6	17·7

The lower temperatures and greater heights of the tropopause in summer are presumably due to the stronger convection in the troposphere in that season.

The persistent increase of temperature with height for at least 5 km. above the tropopause in the tropics finds a natural explanation if we assume that the tropopause marks the lower limit of the ozone layer in the atmosphere.

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Distribution of Potential Temperature in the First 25 Kilometres over the Northern Hemisphere.

In his communication in Nature of June 15, p. 906, Sir Napier Shaw has emphasised the fundamental importance of a knowledge of the distribution of entropy in the atmosphere for an understanding of the physics of the general circulation.

In Fig. 1 is drawn a smoothed diagram (similar to Sir Napier Shaw's diagram on p. 116 of his "Manual of Meteorology", vol. 2) showing the latitudinal distribution of potential temperature in summer and winter of the northern hemisphere. The potential temperatures plotted (in degrees absolute) are

o 1

Nature, 124, 509–510, 1929.

temperatures which the air at any place would assume if compressed or expanded adiabatically to 1000 mb. The temperature data used in the calculation are the same as those employed in preparing the diagram of temperature distribution over the earth (see NATURE, June 1, p. 834), and the monthly mean surface pressure data at the places of sounding balloon observations are taken from the isobaric maps given in pp. 218-241 of the book quoted above. The values obtained from the results of a few sounding balloon ascents over Poona (lat. 18° N.) during the winter of 1928–29 have also been used. As is well known, lines of equal potential temperature are also lines of equal entropy.

It is possible that potential temperatures over north India during the summer are exceptionally high and that the trough near Lat. 25° N. will be less marked if more data from similar latitudes in other parts of the world are available.

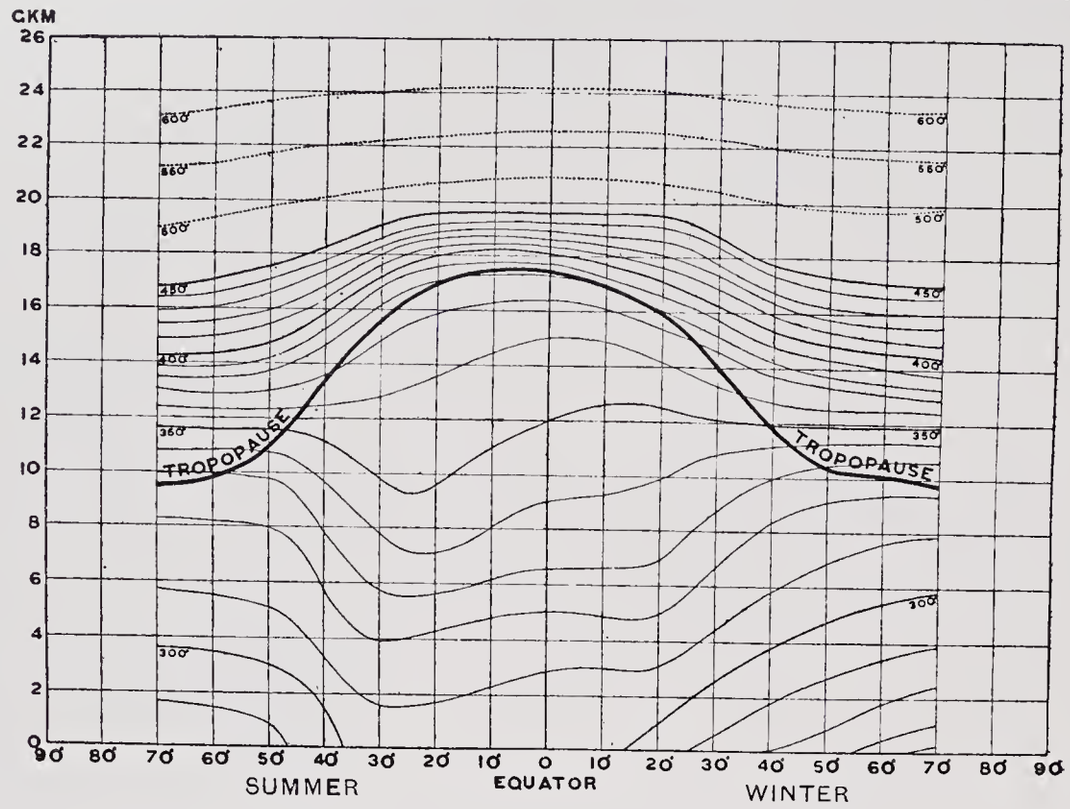

FIG. 1.—Upper air potential temperatures over the northern hemisphere.

Two interesting features (also partially shown in Sir Napier Shaw's diagram) may be pointed out :

1. The dip in the isentropics over the tropics and sub-tropics below about 12 gkm., their elevation between 12 gkm. and 20 gkm., and their pronounced concentration between 17 gkm. and 20 gkm., especially during the summer, suggest that these features are causally connected.

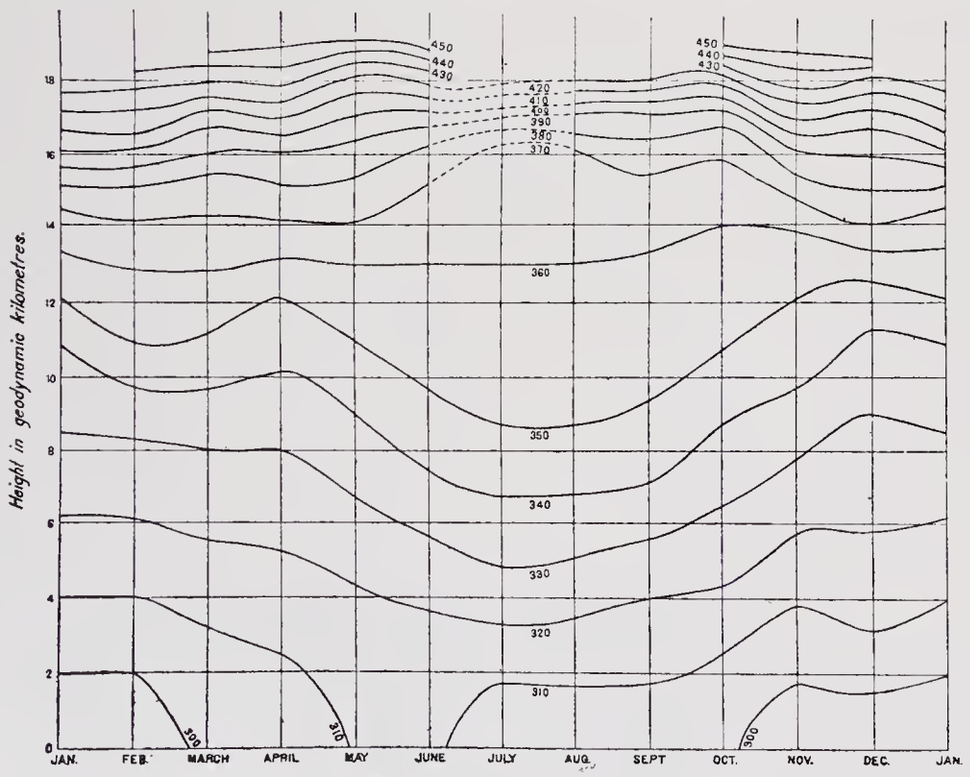

FIG. 2.—Annual variation of potential temperature with height at Agra.

2. Within the tropics during summer the isentropic lines have a downward slope towards the north practically throughout the troposphere, while between 30° N. and 50° N. they have an upward slope to about 12 gkm. Tropical storms and depressions occur mostly in the neighbourhood of this V-shaped trough in the isentropics and move from an easterly direction in the region where the isentropics fall towards the north and from a westerly direction in the region where they rise.

In connexion with Fig. 1, it may be interesting to point out the close analogy which the distribution of potential temperature in Fig. 1 bears to the seasonal variation of its distribution over Agra (Fig. 2). The influence of the high value of entropy below 12 gkm. in raising the tropopause and increasing the inversion above it is clear in both cases.

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DISCUSSION OF RESULTS OF SOUNDING BALLOON ASCENTS AT AGRA DURING THE PERIOD JULY 1925 TO MARCH 1928 AND SOME ALLIED QUESTIONS.

BY

K. R. Ramanathan, M.A., D.Sc.

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Summary.—In this paper, the monthly mean data of temperature, humidity and pressure, and derived quantities like lapse-rate, density and potential temperature obtained from sounding balloon ascents at Agra during the period July 1925—March 1928 are analysed and discussed. Mean monthly pressure differences at different levels between Agra and Europe are considered in their relation to upper wind circulation. The different types of transition from troposphere to stratosphere over Agra are analysed and the seasonal variation of the height and temperature of the tropopause discussed. The complementary nature of the variation of these quantities at Agra and Batavia is pointed out. Diagrams are given showing the probable distribution of temperature and potential temperature in the first 25 km. of the atmosphere over the northern hemisphere in summer and winter.

1. INTRODUCTION.

In Volume XXIV, Part VI of the Memoirs of the Indian Meteorological Department, Dr. Harwood has analysed the data of upper air temperatures and humidities obtained from an earlier series of ascents of sounding balloons at Agra during the period 1915-18. The observations of the period under discussion in this paper (July 1925—March 1928) were obtained under the direction of Mr. G. Chatterjee, M.Sc., Meteorologist in charge of the Upper Air Observatory, Agra. Mr. Chatterjee has devised various improvements in the technique of sounding balloon work at Agra which have resulted in greater accuracy of the records. Owing to the introduction of rubber and vultex balloons, the maximum

Mem. Ind. Met. Dept. 25(5), 163–193, 1930.

heights attained in the present series of ascents were generally greater than in the older series and much new information has been obtained regarding layers above 10 km. The author had the advantage of working with Mr. Chatterjee at the Upper Air Observatory, Agra, during the period, January 1927 to April 1928.

The total number of records used in the present discussion is 89. The manner in which these flights are distributed in the different years and months is shown in table 1.

TABLE 1.

Year.	Jan.	Feb.	Mar.	Apl.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL.
1925	..	..	..	..	..	..	1	2	3	1	0	0	7
1926	3	0	2	5	2	5	2	3	4	2	4	1	33
1927	2	2	2	3	3	3	1	3	3	9	4	3	38
1928	4	2	5	..	..	..	..	..	..	..	..	..	11
TOTAL . .	9	4	9	8	5	8	4	8	10	12	8	4	89

The distribution of the ascents according to the time of the day is shown in Table 2.

TABLE 2.

	TIME IN HRS. I. S. T.						
	15—16.	16—17.	17—18.	18—19.	19—20.	21—22.	TOTAL.
Number of ascents . .	1	5	33	42	7	1	89

The data of the individual ascents in 1926 and 1927 are given in the respective Annual Summaries of the Indian Meteorological Department, those for 1925 in Appendix C of this paper and those for 1928 will appear in part 14 of Upper Air Data, 1928.

The units used for temperature are degrees absolute on the Centigrade scale, for pressure millibars and for height above sea-level geodynamic kilometres. The unit for lapse-rate is therefore naturally degrees per geodynamic kilometre. For comparison with previous results and results obtained in other parts of the world, tables of temperature, pressure and density are also given for geometric kilometres in Appendix B.

2. TEMPERATURE.

In Table 3 are given the monthly and annual mean temperatures with the number of observations at each level on which the means are based. Up to 3 gkm, the values are given for each half gkm. step and thereafter for each integral gkm. In calculating heights from pressures and temperatures, allowance has been made for humidity.

TABLE 3.—MEAN MONTHLY TEMPERATURES AT DIFFERENT HEIGHTS (GEODYNAMIC).

[*T=Temperature in degrees A, n=number of observations.*]

Height in gkm.	January.		February.		March.		April.		May.		June.	
	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*
20	212·5	*1*	215·5	*1*	198·5	*1*	212·0	*2*	209·5	*1*	..	..
19	208·0	*1*	213·5	*1*	202·5	*2*	206·0	*6*	202·5	*3*	204·5	*1*
18	203·5	*3*	208·0	*3*	202·5	*3*	204·5	*6*	197·5	*3*	201·5	*4*
17	203·0	*3*	205·5	*3*	200·0	*4*	203·0	*6*	199·0	*4*	197·5	*6*
16	203·5	*4*	205·0	*3*	202·5	*5*	202·0	*5*	202·0	*4*	197·5	*6*
15	203·5	*4*	205·5	*3*	205·0	*5*	206·0	*5*	207·0	*4*	204·0	*6*
14	207·0	*5*	210·0	*3*	210·5	*5*	210·5	*6*	212·5	*5*	210·5	*6*
13	212·0	*5*	215·0	*3*	217·0	*5*	214·5	*6*	217·5	*5*	218·0	*6*
12	217·5	*5*	222·5	*3*	223·5	*6*	219·0	*6*	224·0	*5*	226·0	*6*
11	222·5	*6*	228·0	*3*	228·5	*7*	226·0	*7*	231·0	*5*	235·0	*7*
10	227·5	*6*	233·5	*3*	234·5	*7*	232·0	*7*	238·5	*5*	243·0	*8*
9	236·5	*7*	236·5	*3*	240·7	*7*	239·0	*7*	245·0	*5*	251·0	*8*
8	244·0	*7*	243·5	*3*	246·0	*8*	246·0	*7*	252·0	*5*	257·5	*8*
7	250·5	*7*	251·0	*3*	253·0	*9*	253·5	*7*	258·5	*5*	263·0	*8*
6	257·0	*8*	256·5	*4*	260·0	*9*	260·0	*7*	264·5	*5*	268·0	*8*
5	263·5	*8*	263·0	*4*	266·5	*9*	267·0	*8*	271·0	*5*	274·0	*8*
4	270·0	*8*	269·0	*4*	273·5	*9*	273·5	*8*	278·5	*5*	280·0	*8*
3	276·0	*8*	273·0	*4*	280·0	*9*	281·5	*8*	287·0	*5*	287·0	*8*
2·5	278·0	*9*	276·5	*4*	283·5	*9*	285·5	*8*	292·0	*5*	291·5	*8*
2	280·5	*9*	280·5	*4*	287·0	*9*	290·0	*8*	296·5	*5*	296·0	*8*
1·5	283·0	*9*	284·0	*4*	291·0	*9*	294·0	*8*	301·0	*5*	300·0	*8*
1	286·5	*9*	288·0	*4*	295·0	*9*	298·0	*8*	305·5	*5*	305·0	*8*
0·5	289·5	*8*	291·5	*4*	299·0	*9*	302·0	*8*	309·0	*5*	308·0	*8*
Surface (0·17).	290·5	*9*	293·0	*4*	301·5	*9*	302·5	*8*	309·0	*5*	310·5	*8*

C

TABLE 3.—MEAN MONTHLY TEMPERATURES AT DIFFERENT HEIGHTS (GEODYNAMIC)—*contd.*

[*T=Temperature in degrees A, n=number of observations*]—contd.

Height in gkm.	July.		August.		September.		October.		November.		December.		Annual mean.	Range.
	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	
20	..	..	..	..	..	..	..	..	208·5	2	..	..	..	..
19	..	..	..	..	..	..	205·0	1	205·5	3	207·0	1	..	..
18	..	..	201·0	2	200·0	3	197·0	5	204·0	4	202·0	2	201·2	11·0
17	..	..	194·0	2	194·5	3	191·5	5	203·5	5	199·5	2	198·9	14·0
16	..	..	194·5	2	196·5	4	194·5	5	201·5	5	202·5	3	199·8	10·5
15	..	..	203·0	3	202·5	4	201·5	6	204·0	5	207·5	3	204·4	5·5
14	209·5	1	210·5	4	209·5	4	208·0	6	206·0	5	210·5	3	209·6	6·5
13	219·5	2	219·5	4	218·5	5	216·0	7	211·5	5	211·0	4	215·8	8 5
12	230·0	2	229·5	5	226·5	5	223·5	9	219·0	5	216·0	4	223·0	14·0
11	239·0	2	238·0	5	236 5	7	231·5	10	227·0	6	221·0	4	230·3	18·0
10	247·3	2	246·0	7	243·5	7	239·0	10	234·0	7	228·0	4	237·3	20·0
9	254·0	3	253·5	8	251·5	8	245·5	11	241·0	8	236·0	4	244·1	18·0
8	260·0	3	260 5	8	259·0	8	252·5	11	246·5	8	244·5	4	251·0	17·0
7	266·0	3	266·0	8	264·5	8	259·0	11	252·5	8	251·5	4	257·4	15·5
6	272·0	4	271·0	8	270·0	8	265·5	11	259·0	8	259·0	4	263·6	15·5
5	277·5	4	277·0	8	273·5	10	271·0	12	265·5	8	266·0	4	269·6	14·5
4	282·5	4	281·5	8	279·0	10	277·0	12	270·5	8	273·5	4	275·7	13·5
3	287·0	4	286·3	8	284·5	10	282·0	12	276·5	8	279·0	4	281·2	14·0
2·5	289·0	4	289·0	8	287·5	10	285·0	12	279·0	8	282·0	4	284·9	15·5
2	291·5	4	291·5	8	291·0	10	289·0	12	282·0	8	284·0	4	288·3	16·0
1·5	294·0	4	294·5	8	294·5	10	293·5	12	284·5	8	285·0	4	291·6	18·0
1	296·0	4	298·0	8	298·0	10	297·5	12	288·0	8	288·5	4	295·3	19·0
0·5	299·0	4	301·0	8	300·5	10	301·0	12	291·0	8	291·5	4	298·6	19·5
Surface (0·17).	301·0	4	302·5	8	300·5	10	300·5	12	293·0	8	293·5	4	299·8	20·0

Fig. 1 shows the annual variation of temperature at different heights over Agra.

From the surface to 3 gkm. the highest mean temperatures occur in May and June, from 4 to 13 gkm. in July-August and from 16 to 20 gkm. in February. At 14 and 15 gkm., there is no pronounced maximum or minimum in any month. The highest temperatures up to 3 gkm. thus occur in a part of the year which is recognised as the hot season in north-west India, while from 4 to 13 gkm. they occur during the active monsoon season. During the latter season, although the lower atmosphere is cooled by the frequent rains and attendant humidification, a large amount of heat is liberated in the atmosphere above the level of low clouds by the condensation of water-vapour and the absorption of solar radiation in the moist atmosphere. The lowest mean temperatures up to 2 gkm. occur in January, from 2·5 to 8 gkm. in February, from 9 to 13 gkm. in December and from 15 to 18 gkm. in October. Some of these conclusions may have to be slightly modified when more data have accumulated.

The range of variation of the monthly mean temperatures during the year decreases from a maximum of 20°C at the surface to 13°·5C at 4 gkm. and increases above that level to a second maximum of 20°C at 10 gkm. The range is lowest (4°·5C) at 15 gkm. and increases again above that level, but owing to the smallness of the number of observations the change from level to level is not regular. The minimum range at 4 gkm. and the increase of range from 4 to 10 gkm. are due to the facts that during the hot months of the year, the lapse-rate of temperature is very high from the surface up to 4 gkm. and above this height, there is a more or less sharp decrease in lapse-rate; and that during the months June to August when the temperature at 4 gkm. is highest, the height-temperature curve between 4 and 10 gkm. follows approximately the curve of saturation adiabatic and hence the lapse-rates are generally smaller than in the drier months. The same reason is responsible for the decrease of range above 10 gkm. to 15 gkm. The saturation adiabatic in this region becomes (owing to the low temperature) practically identical with the dry-air adiabatic and hence the lapse-rates in the monsoon are larger than in the other months. Table 3(*a*) shows the differences between the temperatures given in Table 3 above and those interpolated at the corresponding geodynamic levels from Table 9 of Harwood's paper (denoted respectively by (R) and (H)). The differences are given to the nearest 0·5°C.

TABLE 3(*a*).—TEMPERATURE DIFFERENCES (R)—(H).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
11	1·0	2·5	—2·0	—4·0	—0·5	—4·0	0·5	4·0	2·0	—4·0	—1·0	—7·5
10	3·0	2·5	—1·0	—0·5	5·0	—1·5	3·0	4·0	1·5	—1·5	—2·0	—5·5
9	6·5	—0·5	—1·0	1·5	6·5	0·0	3·0	4·5	2·0	0·0	—1·5	—1·5
8	7·0	—1·0	0·0	2·5	5·5	0·0	2·5	5·0	3·0	1·0	—2·0	1·5
7	6·0	1·0	2·5	2·5	4·5	—1·0	2·5	5·0	2·5	1·0	—3·5	2·5
6	5·5	1·0	3·5	2·5	3·0	—1·5	3·0	3·5	2·0	1·0	—3·5	3·5
5	4·0	0·0	3·0	3·0	2·5	0·0	3·5	3·0	—0·5	0·5	—2·0	3·0
4	3·5	0·0	4·0	2·0	3·5	0·5	3·0	2·0	—1·0	0·5	—2·5	3·0
3	2·5	—2·5	5·5	3·0	5·5	1·0	2·0	1·5	0·0	0·0	—4·5	2·5
2	0·0	—2·0	4·5	2·5	7·0	3·0	1·0	1·0	1·5	2·5	—3·5	2·5
1	0·5	—2·0	5·0	2·0	8·0	5·5	—1·0	2·0	2·0	3·0	—1·0	—0·5
Surface (0·17)	0·0	—0·5	12·5	1·0	8·0	5·5	—1·0	4·0	0·5	3·0	1·0	8·0

It will be seen that some of these differences exceed 5°C, but this is not surprising when we take note of (1) the total number of observations used in each series for making up

the means and (2) the differences in the times of ascent. Harwood's means for January and March were obtained from 2 and 3 observations respectively and for February and December from 4 observations each. There were again only 4 observations in the present series for February, July and December. These numbers refer to the lower levels; with increase of height, there is a further decrease in number particularly in the earlier series owing to the shortness of the flights. It will also be seen from Table 2 of this paper and Table 13 of Harwood's that while practically all the ascents in the present series were in the afternoon, a large proportion of those in the former series were made in the morning. For example, 2 out of 3 successful ascents in March, 3 out of 6 in May and 5 out of 11 in June in the earlier series were made at 5 hrs. in the morning. Owing to the greater homogeneity of the conditions under which the present series of ascents were made, it was thought not desirable to average the data of the two series.

3. LAPSE-RATES.

The mean monthly values of lapse-rates in different layers are given in Table 4.

TABLE 4.—MEAN MONTHLY LAPSE-RATES IN DEGREES CENTIGRADE PER GEODYNAMIC KILOMETRE.

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean.
20	..	..	..	..	..	..	..	..	..	..	..	..	..
19	—4·4	—2·1	2·0	—4·7	—4·9	..	..	..	..	..	—4·5	..	—3·1
18	—2·8	—5·1	—0·7	—1·4	—5·1	—5·2	..	..	..	—9·7	—2·1	—6·7	—4·3
17	—0·4	—2·7	—2·3	—1·3	—0·9	—4·5	..	—6·7	—5·5	5·6	—1·1	—2·7	—3·1
16	1·1	—0·5	2·3	—0·2	3·3	0·1	..	0·6	2·1	3·1	—2·0	3·7	1·1
15	—0·1	0·7	2·4	3·9	4·7	6·4	..	8·2	5·9	6·1	2·3	4·9	4·1
14	3·3	4·4	5·8	4·1	4·3	6·9	..	8·6	6·9	6·8	2·0	3·1	5·1
13	5·1	5·3	6·5	4·3	5·0	7·6	8·6	8·9	8·9	8·3	5·9	2·5	6·3
12	5·2	7·3	6·1	4·3	6·2	7·9	10·5	9·2	8·0	7·9	7·2	5·1	7·1
11	5·2	4·8	5·2	6·6	7·2	8·6	8·9	8·5	8·8	7·7	7·3	4·9	7·0
10	5·3	5·7	5·9	6·2	7·6	7·9	8·3	7·7	6·9	7·3	7·4	7·2	6·9
9	6·9	3·0	6·1	7·2	6·5	8·0	6·3	7·6	7·8	6·8	7·1	7·6	6·7
8	7·3	5·9	5·9	6·9	7·0	6·4	6·3	6·9	7·1	7·1	5·5	8·6	6·7
7	6·5	7·6	6·6	7·1	6·3	5·5	5·7	5·2	5·9	6·4	5·7	7·6	6·3
6	5·2	5·9	6·9	6·5	6·1	5·1	5·8	5·2	5·4	6·6	6·8	7·6	6·1
5	6·4	6·4	6·7	7·2	6·4	5·9	5·6	5·9	4·6	6·0	6·4	6·9	6·2
4	6·4	6·4	6·9	6·2	7·7	5·9	5·1	4·7	5·3	5·5	5·2	7·3	6·1
3	6·0	3·7	6·4	8·0	8·4	7·4	4·3	4·8	5·4	5·0	5·7	5·8	5·9
2·5	4·5	6·3	7·1	7·9	9·4	8·6	4·0	5·1	6·3	5·8	5·7	5·7	6·4
2	5·5	7·4	7·3	8·9	9·2	8·8	4·3	4·8	6·5	8·5	6·1	4·0	6·8
1·5	5·0	5·9	7·6	8·5	9·4	8·4	4·9	6·3	7·1	8·2	4·6	2·5	6·5
1	6·4	7·0	7·3	8·3	8·8	8·8	5·5	6·7	7·1	8·8	6·8	6·1	7·3
0·5	5·7	5·9	8·5	3·8	8·2	7·6	6·0	5·7	5·3	6·7	5·5	6·1	6·3

For discussing lapse-rates, it is convenient to divide the year into seasons. From the point of view of upper air conditions, the year may be divided into—

(1) Winter—November to February.
(2) Early hot season—March and April.
(3) Later hot season or pre-monsoon period—May and June.
(4) Monsoon season—July and August.
and (5) Post-monsoon period—September and October.

The seasonal mean values of temperatures and lapse-rates arranged according to the above division of the year into seasons are given in table 5.

TABLE 5.—SEASONAL MEAN VALUES OF TEMPERATURES AND LAPSE-RATES.

Height in gkm.	Temperatures (°A).					Height in gkm.	Lapse-rates (°C/gkm.)				
	Nov., Dec., Jan., Feb.	Mar., April.	May, June.	July, Aug.	Sept., Oct.		Nov., Dec., Jan., Feb.	Mar., April.	May, June.	July, Aug.	Sept. Oct.
20	212·0	205·5	209·5	..	..	..	..	..	..	..	..
19	208·5	204·5	203·5	..	205·0	19 —20	—3·3	—1·4	—4·9	..	..
18	204·5	203·5	199·5	201·0	198·5	18 —19	—4·6	—1·1	—5·1	..	—9·7
17	203·0	201·5	198·0	194·0	193·0	17 —18	—1·7	—1·8	—2 7	—6 7	—5·5
16	203·0	202·5	200·0	194·5	195·5	16 —17	0·6	1·1	1·7	0·6	2·6
15	205·0	205·5	205·5	203·0	202·0	15 —16	2·0	3·2	5·5	8·2	6·0
14	208·5	210·5	211·5	210·0	209·0	14 —15	3·3	4·9	5·6	8·6	6·9
13	212·5	215·5	217·5	219·5	217·0	13 —14	4·7	5·4	6·3	8·7	8·1
12	219·0	221·5	225·0	230·0	225·0	12 —13	6·2	5·2	7·1	9·9	7·9
11	224·5	227·5	233·0	238·5	234·0	11 —12	5·6	5·9	7·9	8·7	8·3
10	231·0	233·5	241·0	247·0	241·0	10 —11	6·4	6·1	7·7	8·0	7·1
9	237·5	239·5	248·0	254·0	248·5	9 —10	6·2	6·7	7·3	6·9	7·3
8	244·5	246·0	255·0	260·0	256·0	8 — 9	6·6	6·4	6·7	6·6	7·1
7	251·5	253·5	261·0	266·0	262·0	7 — 8	6·9	6·9	5·9	5·5	6·1
6	258·0	260·0	266·0	271·5	268·0	6 — 7	6·4	6·7	5·6	5·5	6·0
5	264·5	267·0	272·5	277·0	272·0	5 — 6	6·5	7·0	6·1	5·7	5·3
4	271·0	273·5	279·0	282·0	278·0	4 — 5	6·3	6·6	6·8	4·9	5·4
3	276·0	281·0	287·0	287·0	283·0	3 — 4	5·3	7 2	7·9	4·5	5·2
2·5	279·0	284·5	291·5	289·0	286·0	2·5— 3	5·6	7·5	9·0	4·5	6·1
2	281·5	288·5	296·0	291·5	290·0	2 — 2·5	5·8	8·1	9·0	4·5	7·5
1·5	284·0	292·5	300·5	294·0	294·0	1·5— 2	4·5	8·1	8·9	5·6	7·7
1	287·5	296·5	305·5	297·0	297·5	1 — 1·5	6·6	7·8	8·8	6·1	7·9
0·5	291·0	300·5	308·5	300·0	301·0	0·5— 1	5·8	6·2	7·9	5·9	6·0
Surface (0·17).	292·5	302·0	310·0	302·0	300·5	..	..	..	..	..	..

D

The variation of the average lapse-rate with height in each season is shown in fig. 2.

(1) During the winter, there is generally a layer of well-marked maximum lapse-rate between 1 and 1·5 gkm. Above 4 gkm., the mean lapse-rate slowly increases with height reaching a feeble maximum between 7 and 8 gkm. and then decreases slowly up to 13 gkm. and rapidly thereafter.

(2) In March and April (and especially in the latter month), the mean lapse-rates are markedly higher up to 4 gkm., than at higher levels, the maximum values on the average of the two months exceeding 8°C/gkm. between 1·5 and 2·5 gkm.[1] There is a feeble minimum of 6·5°C/gkm. between 4 and 5 gkm. The general course of the curve between 4 and 11 gkm. is similar to that of the winter curves, the slight differences being probably attributable to the smallness of the number of observations. The marked decrease in lapse-rate becomes manifest only above 15 gkm.

(3) The curve for the pre-monsoon period is remarkable for its double maximum, one going up to 9°C/gkm. between 1·5 and 3 gkm. and the other to 8°C/gkm. between 11 and 12 gkm. A minimum value of 5·5°C/gkm. occurs between 6 and 7 gkm.

The sudden decrease of lapse-rate marking the top of the troposphere occurs only above 16 gkm. and is sharper than in periods (1) and (2).

(4) The monsoon curve presents some new features. The changes from the hot season are most marked below 5 gkm. The lapse-rates are much smaller below this level than in the hot season, the lowest values being between 2 and 5 gkm. and less than 5°C/gkm. Below 2 gkm., the values are about 6°C/gkm. Above 5 gkm. the values increase (with a probable minimum between 7 and 8 gkm.) to a maximum of 9°C gkm. between 12 and 13 gkm. The sharp decrease of lapse-rate begins at about 16 gkm.

Although the number of observations are few especially in the higher layers, it is not likely that the general conclusions will be appreciably modified by further observations as the differences between the values obtained from the individual flights in this season are small.

(5) The monsoon generally withdraws from the United Provinces by the middle of September. The lapse-rate curve of September-October is intermediate in character between that for May-June and that for the monsoon. The two regions of maximum lapse-rates occur between 1 and 2 gkm. and between 11 and 14 gkm. The minimum occurs between 3 and 5 gkm. The decrease of lapse-rates above 14 gkm. is more gradual than in July-August.

The relative frequencies with which different lapse-rates occur in different layers in all the seasons are shown in Table 6. The steadiness of the values in May-June and July-August is remarkable. Although we are not dealing with the same number of observations in different layers and in different seasons, we may safely conclude that the scatter of lapse-rates in all layers is greatest during the winter.

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[1] The smaller lapse-rate below 1·5 gkm. is probably due to the fact that the soundings were generally made after 17 hrs. and cooling due to radiation had set in at the surface.

Table 6.—Seasonal Frequencies of lapse-rates.

(*a*) *November, December, January and February.*

Height in gkm.	Number of observations.	Range of lapse-rates.													
		−3·0.	−3·0 to −2·1.	−2·0 to −1·1.	−1·0 to −0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
20 —21	2	1	1	..	..	..	..	..	..	..	..	..	..	..	..
19 —20	4	3	1	..	..	..	..	..	..	..	..	..	..	..	..
18 —19	6	3	1	1	1	..	..	..	..	..	..	..	..	..	..
17 —18	12	5	1	1	1	3	1	..	..	..	..	..	..	..	..
16 —17	13	2	2	2	1	1	1	2	..	1	1	..	..	..	..
15 —16	15	..	..	3	1	1	4	2	..	2	1	..	..	..	..
14 —15	15	..	..	..	1	3	..	5	1	2	1	1	1	..	..
13 —14	16	..	..	..	..	..	2	2	2	3	4	..	1	1	1
12 —13	17	..	..	..	..	..	1	1	..	2	3	4	5	..	1
11 —12	17	..	..	..	..	..	1	..	2	3	4	3	2	2	..
10 —11	19	..	..	..	..	..	..	1	..	3	1	8	4	1	1
9 —10	20	..	..	..	..	..	1	2	..	1	3	3	4	4	2
8 — 9	22	..	..	..	..	1	1	..	..	3	3	1	5	7	1
7 — 8	22	..	..	..	..	..	..	2	..	1	5	4	5	4	1
6 — 7	22	..	1	..	..	..	..	..	1	1	5	5	7	2	..
5 — 6	24	..	..	..	..	..	..	..	1	3	4	9	4	2	1
4 — 5	24	..	..	..	..	1	..	..	..	2	6	8	7	..	..
3 — 4	24	..	..	..	..	..	1	1	2	4	10	3	1	1	1
2·5— 3	24	..	1	..	..	..	..	2	3	3	4	6	4	..	1
2 — 2·5	25	..	..	..	..	..	1	2	2	5	6	2	2	4	1
1·5— 2	25	1	1	..	..	1	1	2	3	3	4	3	3	2	1
1 — 1·5	24	..	..	..	..	..	1	..	3	2	4	3	7	2	2
0·5— 1	22	..	..	..	..	1	..	1	2	1	8	3	4	2	..

(*b*) *March and April.*

22 —23	1	..	1	..	..	..	..	..	..	..	..	..	..	..	..
21 —22	1	..	1	..	..	..	..	..	..	..	..	..	..	..	..
20 —21	1	..	..	1	..	..	..	..	..	..	..	..	..	..	..
19 —20	3	1	1	..	..	..	1	..	..	..	..	..	..	..	..
18 —19	8	..	2	3	..	3	..	..	..	..	..	..	..	..	..
17 —18	9	1	3	2	1	1	1	..	..	..	..	..	..	..	..
16 —17	9	1	..	1	..	3	1	1	1	1	..	..	..	..	..
15 —16	10	..	..	..	1	..	3	..	2	2	1	1	..	..	..
14 —15	9	..	..	..	..	..	1	1	..	3	1	3	..	..	..
13 —14	11	..	..	..	..	..	..	1	3	1	1	3	2	..	..
12 —13	11	..	..	..	..	..	2	..	1	2	2	2	..	2	..
11 —12	12	..	..	..	..	..	2	..	1	1	1	2	2	2	1
10 —11	14	..	..	..	..	..	..	..	1	4	3	2	1	2	1
9 —10	13	..	..	..	..	..	1	..	..	1	1	3	5	1	1
8 — 9	14	..	..	..	..	..	..	..	..	2	5	3	3	1	..
7 — 8	15	..	..	..	..	..	..	..	..	1	2	6	2	3	1
6 — 7	16	..	..	..	..	..	..	..	..	1	2	6	6	1	..
5 — 6	16	..	..	..	..	..	..	..	..	1	3	6	3	2	1
4 — 5	16	..	..	..	..	..	1	..	..	1	3	5	5	1	..
3 — 4	17	..	..	..	..	..	..	..	1	1	3	4	2	2	4
2·5— 3	17	..	..	..	..	..	..	..	1	1	2	1	5	5	2
2 — 2·5	16	..	..	..	..	..	..	..	..	..	2	1	7	4	2
1·5— 2	16	..	..	..	..	..	..	..	..	1	1	1	2	7	4
1 — 1·5	14	..	..	..	..	..	..	..	..	1	1	2	3	7	—
0·5—1	16	..	..	..	..	..	..	..	..	1	1	3	2	4	5

TABLE 6.—SEASONAL FREQUENCIES OF LAPSE-RATE—*contd.*

(c) *May and June.*

Height in gkm.	Number of observations.	Range of lapse-rates.													
		<−3·0.	−3·0 to −2·1.	−2·0 to −1·1.	−1·0 to −0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
19 —20	2	1	1	..	..	..	..	..	..	..	..	..	..	..	..
18 —19	4	4	..	..	..	..	..	..	..	..	..	..	..	..	..
17 —18	7	3	1	2	..	1	..	..	..	..	..	..	..	..	..
16 —17	10	2	1	..	..	..	1	2	2	1	1	..	..	..	..
15 —16	10	..	..	..	..	..	..	1	1	4	..	1	..	2	1
14 —15	10	..	..	..	1	..	..	..	..	..	3	4	1	1	..
13 —14	11	..	..	1	..	..	..	..	..	..	1	4	4	1	..
12 —13	11	..	..	..	..	..	..	1	..	..	..	3	4	3	..
11 —12	11	..	..	..	..	..	..	..	..	..	..	2	4	4	1
10 —11	12	..	..	..	..	..	..	..	..	..	..	2	6	4	..
9 —10	13	..	..	..	1	..	..	..	..	..	..	1	6	4	1
8 — 9	13	..	..	..	..	..	..	..	..	..	4	5	3	1	..
7 — 8	13	..	..	..	..	..	..	..	..	4	5	2	1	1	..
6 — 7	13	..	..	..	..	..	1	..	1	2	4	2	2	..	..
5 — 6	13	..	..	..	..	..	..	..	..	3	4	3	3	..	..
4 — 5	13	..	..	..	..	..	..	..	..	3	2	3	3	1	1
3 — 4	13	..	..	..	..	..	..	..	..	1	..	2	4	6	..
2·5— 3	13	..	..	..	..	..	..	..	..	..	1	..	1	4	7
2 — 2·5	13	..	..	..	..	..	..	..	..	..	..	..	1	7	5
1.5 —2	13	..	..	..	..	..	..	..	..	..	..	1	..	8	4
1 —1·5	12	..	..	..	..	..	..	..	..	..	..	..	1	7	4
0·5—1	12	..	..	..	..	..	..	..	2	..	1	2	4	1	2

(d) *July and August.*

17 —18	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..
16 —17	2	..	..	..	..	2	..	..	..	..	..	..	..	..	..
15 —16	2	..	..	..	..	..	..	..	..	..	..	..	1	1	..
14 —15	3	..	..	..	..	..	..	..	..	..	..	..	1	1	1
13 —14	5	..	..	..	..	..	..	..	..	..	..	..	2	2	1
12 —13	6	..	..	..	..	..	..	..	..	..	..	..	..	1	5
11 —12	7	..	..	..	..	..	..	..	..	..	..	..	2	2	3
10 —11	7	..	..	..	..	..	..	..	..	..	..	1	2	4	..
9 —10	9	..	..	..	..	..	..	..	..	..	..	4	3	2	..
8 — 9	11	..	..	..	..	..	..	..	..	..	1	6	4	..	..
7 — 8	11	..	..	..	..	..	..	..	1	1	8	1	..	..	..
6 — 7	11	..	..	..	..	..	..	..	..	3	8	..	..	..	..
5 — 6	12	..	..	..	..	..	..	..	..	1	9	1	1	..	..
4 — 5	12	..	..	..	..	..	1	1	..	4	5	1	..	..	..
3 — 4	12	..	..	..	..	..	..	..	2	7	2	1	..	..	..
2·5— 3	12	..	..	..	..	..	..	1	1	5	5	..	..	..	..
2 — 2·5	12	..	..	..	..	..	..	1	4	3	2	2	..	..	..
1·5— 2	12	..	..	..	..	..	..	..	1	3	6	..	..	..	2
1 — 1·5	11	..	..	..	..	..	..	..	1	1	3	3	2	..	1
0·5— 1	12	..	..	..	..	..	..	..	1	2	4	2	2	1	..

TABLE 6.—SEASONAL FREQUENCIES OF LAPSE-RATE—*concld.*

(e) September and October.

Height in gkm.	Number of observations.	Range of lapse-rates.													
		<-3·0.	-3·0 to -2·1.	-2.0 to -1·1.	-1·0 to -0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
20 —21	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
19 —20	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
18 —19	1	1	..	..	..	..	..	..	..	..	..	..	..	..	..
17 —18	8	8	..	..	..	..	..	..	..	..	..	..	..	..	..
16 —17	8	..	..	..	1	1	..	3	1	1	1	..	..	..	..
15 —16	9	..	..	..	..	..	..	..	..	3	2	2	1	1	..
14 —15	10	..	..	..	..	..	1	..	..	1	..	4	2	..	2
13 —14	10	..	..	..	..	..	..	..	..	..	..	1	2	6	1
12 —13	12	..	..	..	..	..	..	..	..	..	..	1	4	7	..
11 —12	14	..	..	..	..	..	..	..	..	..	1	1	3	8	1
10 —11	17	..	..	..	..	..	..	..	1	1	3	3	4	4	1
9 —10	17	..	..	..	..	..	..	..	..	2	..	4	8	2	1
8 — 9	19	..	..	..	..	..	..	..	..	..	4	5	7	3	..
7 — 8	19	..	..	..	..	..	..	1	1	..	4	8	5	..	..
6 — 7	19	..	..	..	..	..	..	..	..	4	3	8	4	..	..
5 — 6	19	..	..	..	..	..	1	1	2	5	1	6	3	..	..
4 — 5	22	..	..	..	..	..	1	..	2	6	7	2	3	1	..
3 — 4	22	..	..	..	..	..	1	2	3	2	9	3	1	1	..
2·5— 3	22	..	..	..	..	..	..	2	1	3	3	6	5	2	..
2 — 2·5	22	..	..	..	..	..	..	..	1	..	4	3	5	3	6
1·5— 2	22	..	..	..	..	..	..	..	..	3	1	3	3	7	5
1 — 1·5	22	..	..	..	..	..	..	..	..	1	3	..	3	9	6
0·5— 1	20	..	..	..	..	..	1	..	3	2	4	1	7	1	1

4. PRESSURE.

Table 7 gives the monthly mean values of pressure at different heights over Agra. The values have been corrected for humidity. Curves of annual variation are shown in figure 3.

TABLE 7.—MEAN MONTHLY PRESSURES (mb).

Height in gkm.	Jan.	Feb.	Mar.	Apl.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual mean.	Range.
20	51	51	52	53	53	..	..	..	..	..	52	..	..	..
19	60	61	62	63	64	..	..	..	63	63	61	61	62	..
18	*71*	72	73	73	75	76	..	76	75	74	72	73	74	5
17	*84*	86	87	87	89	90	..	91	90	89	85	87	88	7
16	*100*	101	103	103	106	108	..	108	107	106	101	102	104	8
15	*118*	120	123	122	125	128	..	129	128	126	120	121	124	11
14	*140*	142	145	144	149	151	151	152	152	150	143	143	147	12
13	*166*	167	171	170	175	178	180	180	179	175	169	167	163	14
12	*195*	196	201	200	205	209	211	211	209	206	199	197	203	16
11	*228*	229	234	233	239	242	244	244	244	239	232	231	237	16
10	*265*	*265*	271	271	277	280	283	282	281	277	270	269	274	18
9	311	*310*	315	315	322	323	324	325	324	321	313	314	318	15
8	359	*357*	363	363	369	370	371	372	372	369	361	363	366	15
7	413	*412*	417	418	423	423	423	424	425	422	414	417	419	13
6	474	*471*	479	478	483	482	482	483	484	482	475	479	479	13
5	543	*540*	546	546	550	549	548	549	550	549	543	547	547	10
4	617	*614*	621	621	625	621	619	621	622	623	618	621	620	11
3	702	*700*	704	703	707	703	700	702	704	706	702	705	703	7
2·5	747	*745*	749	748	750	747	*745*	747	748	750	747	750	748	5
2	794	791	796	795	796	791	*789*	792	794	798	795	797	794	9
1·5	845	842	845	844	844	839	*838*	840	842	*847*	845	847	843	9
1	899	896	898	895	895	890	*889*	891	894	899	899	901	896	12
0·5	955	953	952	949	948	*942*	943	944	947	952	954	957	950	15
Surface (0·17)	994	991	989	985	982	*977*	979	980	984	989	993	995	987	18

The results up to 11 gkm. are in general agreement with those found by Harwood. At the surface the minimum pressure occurs in June and between 1 and 3 gkm. in July. The maximum at the surface occurs in December. The epochs of maximum and minimum are practically reversed at a height of 6 gkm., with the former occurring in the period May to October and the latter in winter. Between 2 and 5 gkm., there are two minima in the year, one in the winter and the other in July. Above 6 gkm., the character of the annual variation remains practically the same as at 6 gkm. but the maxima occur definitely in the monsoon months July-September. The range of variation decreases from 18 mb. at the surface to 5 mb. at 2·5 gkm. and then increases to 18 mb. at 10 gkm. Thereafter, it again decreases to 2 mb. at 20 gkm. When the variation at each level is considered as a percentage of the actual mean pressure at that level, it is a maximum between 12 and 17 gkm. with a value of about 8 per cent. and a minimum at 2·5 gkm. with a value of 0·7 per cent.

4*a*. COMPARISON OF PRESSURES IN THE UPPER AIR OVER AGRA, BATAVIA AND EUROPE.

Tables 8 and 9 give the monthly mean differences of pressure in millibars at different levels between Agra and Batavia and Agra and England respectively. The data for Batavia are those given by van Bemmelen[1] and those for England by W. H. Dines[2]. The heights in these tables are geometric and not geodynamic kilometres.

TABLE 8.—MEAN MONTHLY DIFFERENCES OF PRESSURE BETWEEN AGRA AND BATAVIA. BATAVIA—AGRA (mb.).

Height in km.*	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	—1	—1	0	—1	—1	..	..	..	..	0	..	..
19	0	—1	0	—1	—2	—3	..	—2	—1	0	1	—2
18	2	1	1	1	0	—3	..	—3	—1	1	3	0
17	3	2	2	1	0	—3	..	—4	—2	1	5	—1
16	4	4	3	2	1	—4	..	—5	—2	1	6	1
15	7	6	4	5	3	—3	..	—6	—4	1	8	2
14	8	8	5	6	3	—2	—4	—7	—4	1	8	4
13	9	10	6	7	4	—2	—7	—7	—4	2	9	7
12	10	12	7	8	6	—2	—6	—6	—3	2	11	9
11	11	12	7	8	7	—1	—6	—5	—4	2	10	7
10	11	13	7	8	5	0	—5	—4	—3	2	9	7
9	12	14	9	10	5	1	—3	—3	—2	3	12	7
8	12	14	9	10	6	2	—1	—1	—1	4	12	7
7	11	13	9	8	5	3	0	0	—1	3	12	7
6	9	14	6	7	3	3	1	0	—1	3	10	4
5	8	12	5	5	3	3	3	2	1	3	9	3
4	9	12	5	5	3	6	5	4	4	4	9	4
3	6	8	4	5	1	5	8	6	4	3	7	2
2	4	6	2	3	2	7	9	6	5	0	3	1
1	1	4	2	4	5	10	11	9	7	2	1	—1

* Heights in this table are given in geometric kilometres.

[1] *Proc. Kon. Akad. Wetenschappen*, Amsterdam, Vol. 30, p. 1313, (1918).

[2] *Geoph. Mem.* No. 13, London M. O.

TABLE 9.—MEAN MONTHLY DIFFERENCES OF PRESSURE BETWEEN AGRA AND ENGLAND.

AGRA—ENGLAND (mb.).

Height in km.*	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
15	8	10	12	9	10	11	..	11	12	11	6	10
14	11	13	16	13	15	14	12	14	14	14	10	13
13	14	15	19	16	17	17	17	17	18	15	11	14
12	16	17	21	18	19	20	20	19	19	18	17	16
11	19	19	25	21	21	21	20	20	21	20	15	20
10	20	21	26	23	24	21	21	19	21	20	17	22
9	21	21	24	20	24	20	18	19	19	19	15	21
8	21	20	23	20	23	18	16	16	18	19	15	21
7	22	21	23	20	21	16	14	14	17	17	14	21
6	20	17	24	19	20	14	12	13	16	17	13	21
5	20	17	22	18	18	13	9	9	13	15	13	21
4	15	13	19	16	16	8	3	4	8	12	11	17
3	14	12	16	11	12	4	—1	0	6	11	9	14
2	10	9	12	8	7	—2	—5	—2	2	9	9	12
1	3	1	3	—1	—2	—10	—12	—9	—4	4	2	5

* Heights in this table are given in geometric kilometres.

Taking first the difference of pressure between Batavia and Agra, the mean gradient is for westerly winds north of the equator between November and May. The gradient increases to a maximum at 8—9 km. and thereafter decreases to a very small value at 20 km. The present observations do not show the existence of any marked resultant gradient in winter for easterly winds below 2 km. between the equator and Agra which Harwood finds and associates with the north-east monsoon. This may be due to the variable position of the high pressure area over the Deccan in winter at a height of 1 and 2 km. separating the regions of easterly and westerly winds. During the active monsoon months July and August there is a large excess of pressure at the surface at Batavia over that at Agra ; this excess rapidly decreases with height and becomes zero at 7 km. which is in agreement with Harwood's results. Above 7 km. the gradient reverses sign and the maximum gradient for easterly winds north of the equator occurs between 11 and 15 km. Conditions are similar in June and September, but the gradient for easterly winds is generally weaker and the reversal of gradient occurs at a greater height in June. In the transition month October, gradients are generally weak at all levels.

The pressure differences between Agra and England given in table 9 show that the gradient is generally a maximum at some height varying from 7 km. in winter to 11 km. in the monsoon. From Teisserenc de Bort's maps of 4 km. isobars it seems probable that pressures in Asia at the latitude of England are lower than those in England in January and larger in July. The winds between North India and Central Asia near the 4 km. level may therefore be expected to be even stronger in winter and weaker in the monsoon than are indicated by the pressure differences given in the above table.

5. HUMIDITY.

The mean monthly values of relative humidity up to 8 gkm. are given in Table 10. In working up the humidity-traces of the meteorographs it was assumed that the displacement of the humidity-pen was proportional to the relative humidity. There are also reasons to believe that the tension to which the hairs were subjected was in some cases excessive. Owing to these limitations, the humidity-values cannot be considered to have more than qualitative significance.

TABLE 10.—MEAN MONTHLY RELATIVE HUMIDITIES.

Height in gkm.	Jan.		Feb.		Mar.		April.		May.		June.		July.		Aug.		Sept.		Oct.		Nov.		Dec.	
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*
10	..		..		..		..		..		..		81	2	67	6	65	2	..		..		..	
9	..		..		..		..		15	4	..		90	3	73	7	61	3	..		..		..	
8	36	6	..		33	3	23	7	14	4	51	7	90	3	80	7	47	6	23	8	..		..	
7	37	6	41	3	37	7	25	7	15	4	51	8	92	3	80	7	47	6	25	8	35	8	31	4
6	39	6	39	4	52	8	28	7	19	4	56	8	89	4	78	7	54	7	29	10	35	8	31	4
5	40	6	44	5	52	8	27	8	21	4	58	8	88	4	67	7	65	9	33	10	38	8	31	4
4	37	6	48	5	48	8	32	8	26	4	61	8	90	4	66	7	69	9	36	11	47	8	32	4
3	39	6	54	5	51	8	30	8	28	4	56	8	91	4	85	7	66	9	39	11	53	8	36	4
2·5	39	6	57	5	47	8	28	8	25	4	52	8	93	4	92	7	67	9	45	11	51	8	37	4
2	39	6	58	5	44	8	25	8	22	4	45	8	93	4	89	7	68	9	48	11	51	8	39	4
1·5	41	5	61	4	37	8	24	8	20	3	39	8	91	4	82	7	68	9	46	11	52	8	36	3
1	47	4	59	4	38	4	23	6	19	3	37	8	90	4	79	7	64	8	44	11	55	8	38	3
0·5	49	4	69	1	35	2	24	6	..		31	7	89	4	..	..	56	6	43	10	61	5	36	1
Surface (0·17)	51	6	60	5	24	8	25	8	26	4	27	9	89	4	77	5	71	9	45	11	55	8	51	4

It is well-known that the hair hygrometer ceases to function below 250° A. The tabulation of humidity values was therefore generally not continued beyond 1 or 2 km. above the level at which they ceased to change with height. The mean values of the ascending and descending curves were taken.

Even the monthly averages of humidity show considerable differences from those given by Harwood. This is not surprising in view of the limitations of hygrometric measurement as mentioned above, the smallness of the number of observations, and the possible range of variation from day to day or even from year to year.

The maximum humidity at all levels occurs in the monsoon month July. There is a secondary maximum in February due to the passage of western disturbances. The corresponding months found by Harwood are August and January. The progressive increase of humidity during the hot season shown by Harwood's data does not appear in the present figures. The driest months from the point of view of relative humidity appear to be the hot season months April and May and not the winter months November, December and January. The contrast between Harwood's and the present figures for November is very strong and is to some extent influenced by the fact that two of the ascents included in the present discussion were made in wet weather. Even if these days are excluded the present humidity values are higher than Harwood's. In the other winter months also, the present values may be somewhat high owing to the fact that many of the ascents in the winter of 1927-28 were made on " disturbed " days.

Variation of humidity with height in different seasons.

During the winter months, there is generally increased humidity at the surface apparently connected with the ground inversion. In disturbed weather, other maxima of humidity at different levels from 1·5 to 6 gkm. are met with. In the hot season months March-May a maximum of humidity is very frequent at some level between 3 and 5 gkm. Its position marks the top of the surface layer of air with the large lapse-rate of temperature. Conditions are somewhat similar in June before the advent of the monsoon, but in this month, humidities above 4 or 5 gkm. are much higher than in May. In July-August, there are generally two heights of maximum humidity one at 1·5 to 2·5 gkm. and the other at about 7 gkm. marking respectively the heights of low and middle clouds. During times of active monsoon the humidity is generally very high throughout, while during times of weak monsoon, there is usually a comparatively dry layer somewhere between 3 and 6 gkm. As is well known, when a dry layer of the atmosphere is superposed on a moist layer and the whole is raised bodily, conditions will become favourable for instability at the surface of transition between the two layers. It is this characteristic combined with the weakness of the upper winds that probably make the monsoon season in the United Provinces specially favourable for thunderstorms. With the retreat of the monsoon in the latter half of September and in October, the humidity values show a maximum near 2 gkm. associated with a well-marked inversion.

The mean monthly values of vapour pressure and mixing ratio are given in tables 11 and 12.

TABLE 11.—MEAN MONTHLY VALUES OF VAPOUR PRESSURE (mb.).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10	..	..	..	..	..	..	0·5	0·3	0·3	..	..	..
9	..	..	..	..	..	..	1·0	0·8	0·6	..	..	..
8	0·1	..	0·2	0·1	0·1	0·9	1·8	1·7	0·9	0·2	..	..
7	0·3	0·3	0·3	0·3	0·3	1·4	3·1	2·6	1·4	0·5	0·3	0·3
6	0·6	0·6	1·0	0·6	0·6	2·2	5·2	4·0	2·6	0·9	0·6	0·6
5	1·0	1·1	1·8	0·9	1·0	3·7	7·0	5·2	4·0	1·7	1·3	1·0
4	1·7	2·0	2·9	2·0	2·4	6·1	10·7	7·0	6·5	2·9	2·4	2·0
3	3·1	3·1	5·2	3·1	4·4	8·7	14·9	13·0	9·3	4·4	4·4	3·4
2·5	3·4	4·7	5·6	3·7	5·6	10·7	16·9	16·9	10·7	6·1	4·7	4·0
2	4·0	6·1	7·5	4·7	6·5	12·2	19·2	18·0	13·9	8·7	5·6	5·2
1·5	5·2	8·1	7·5	6·1	7·5	13·9	23·1	21·8	18·0	11·4	7·0	5·2
1	7·0	10·0	10·0	7·0	9·3	18·0	24·6	24·6	20·4	13·0	9·3	7·0
0·5	8·7	13·9	11·4	9·3	..	18·0	29·5	..	20·4	15·9	12·2	..
Surface (0·17)	10·0	13·9	8·7	10·0	15·9	18·0	33·3	31·4	26·2	16·9	12·2	12·2

TABLE 12.—MEAN MONTLY VALUES OF MIXING RATIO.

(gms. of water-vapour per kgm. of dry air).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10	..	..	..	..	..	..	1·0	0·8	0·6	..	..	..
9	..	..	..	..	..	..	2·0	1·5	1·1	..	..	..
8	0·3	..	0·3	0·2	0·2	1·4	3·1	2·8	1·4	0·4	..	..
7	0·4	0·5	0·5	0·4	0·4	2·0	4·6	3·9	2·0	0·7	0·5	0·4
6	0·8	0·8	1·4	0·7	0·7	2·8	6·7	5·1	3·4	1·2	0·8	0·7
5	1·2	1·3	2·1	1·1	1·2	4·2	8·1	5·9	4·6	1·9	1·5	1·2
4	1·7	2·0	2·8	2·0	2·4	6·3	10·9	7·1	6·7	2·8	2·4	2·0
3	2·8	2·8	4·6	2·8	3·9	7·8	13·5	11·8	8·3	3·9	3·9	3·0
2·5	2·8	4·0	4·7	3·1	4·7	9·0	14·5	14·5	9·0	5·2	4·0	3·3
2	3·1	5·0	5·9	3·7	5·1	9·7	15·5	14·5	11·0	6·8	4·4	4·1
1·5	3·8	6·0	5·6	4·6	5·6	10·5	17·7	16·5	13·6	8·5	5·2	3·8
1	4·9	7·0	7·0	4·9	6·5	12·8	17·7	17·7	14·5	9·1	6·5	4·9
0·5	5·7	9·2	7·5	6·1	..	12·1	19·9	..	13·7	10·5	8·0	..
Surface (0·17)	6·3	8·8	5·5	6·3	10·2	11·7	21·8	20·5	17·0	10·8	7·7	7·7

6. DENSITY.

The monthly mean values of density are given in table 13. The values have been corrected for humidity.

TABLE 13.—MEAN MONTHLY DENSITIES. (gms. per cubic metre).

Height in gkm.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean.	Range.
20	84	82	91	87	88	..	..	..	..	..	87	..	..	..
19	101	100	105	105	108	109	..	..	..	107	103	103	..	..
18	*121*	*121*	125	124	**132**	131	..	**132**	131	131	123	126	127	11
17	*144*	146	152	149	156	159	..	**163**	161	161	145	151	153	19
16	*171*	172	177	178	183	190	..	**193**	190	191	175	175	181	22
15	*202*	203	209	206	210	219	..	**221**	220	218	205	203	211	19
14	*236*	*236*	240	238	244	250	251	251	**252**	251	242	236	244	16
13	273	*271*	275	276	280	285	**286**	**286**	285	282	278	276	279	15
12	312	*307*	313	318	319	**322**	**319**	320	321	321	317	318	317	15
11	357	*350*	357	359	360	359	355	357	359	359	356	**364**	358	*14*
10	406	*395*	403	407	404	401	398	399	402	403	402	**411**	403	16
9	458	457	457	459	458	458	*443*	446	449	455	452	**463**	455	20
8	513	**517**	514	514	510	500	*496*	497	499	509	510	**517**	508	21
7	574	572	574	575	570	559	*552*	554	559	567	571	**577**	567	25
6	643	640	641	640	636	625	*614*	619	623	632	638	**644**	633	30
5	**717**	714	713	712	706	696	*685*	688	698	704	711	716	705	32
4	**795**	794	789	790	780	770	*758*	765	773	782	**795**	790	782	37
3	884	**891**	874	868	856	849	*843*	848	858	870	882	879	867	48
2·5	934	**937**	917	911	893	*888*	890	893	902	914	930	924	911	49
2	**984**	979	963	953	932	*925*	933	938	943	958	979	975	955	59
1·5	**1,038**	1,030	1,009	997	973	*968*	983	984	988	1,000	1,031	1,033	1,003	70
1	**1,090**	1,079	1,055	1,047	1,017	*1,009*	1,034	1,030	1,035	1,046	1,083	1,085	1,051	81
0·5	**1,145**	1,132	1,104	1,090	1,064	*1,058*	1,085	1,078	1,088	1,094	1,136	1,140	1,101	87
Surface (0·17)	**1,190**	1,173	1,138	1,130	1,100	*1,099*	1,120	1,115	1,130	1,140	1,175	1,175	1,140	**100**

The annual range decreases with increase of height from the surface up to 11 gkm. and increases thereafter, reaching a secondary maximum at 16 gkm. Considered as a percentage of the mean density, the range decreases rapidly from the surface up to 2·5 gkm., then more slowly up to 11 gkm. where it becomes a minimum and increases again to ranges exceeding that at the surface at a height of 16 and 17 gkm. It is interesting to note that over England, the minimum range occurs at a height of 8 km.[1]

[1] S. N. Sen, *Q. J. R. Met. Soc.*, 50, 1924, p. 29.

7. POTENTIAL TEMPERATURE.

The mean monthly dry-air potential temperatures are given in table 14.

TABLE 14.—MEAN MONTHLY POTENTIAL TEMPERATURES.
(0A ; standard pressure being 1000 mb.).

Height in gkm.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean.	Range.
20	..	..	..	..	462	..	..	..	..	..	..	..	462	..
19	..	..	452	452	448	452	..	..	..	455	454	466	454	..
18	436	433	430	434	*416*	424	..	421	420	*416*	435	429	427	20
17	415	417	405	411	400	395	..	*389*	390	385	413	405	402	28
16	397	397	389	389	386	376	..	*369*	375	371	390	391	385	28
15	377	379	376	378	377	369	..	*364*	367	366	375	382	374	18
14	365	369	367	368	369	363	361	362	362	*360*	361	370	365	10
13	357	361	361	358	360	360	361	360	359	358	*354*	*354*	359	7
12	349	356	356	349	353	356	361	359	356	354	350	*346*	354	15
11	341	350	348	345	350	354	360	357	356	351	347	*338*	350	22
10	*334*	343	342	339	346	351	357	355	352	347	341	*334*	345	23
9	332	333	336	334	340	348	351	351	349	341	338	*330*	340	21
8	*328*	329	330	330	337	344	347	347	345	337	331	*328*	336	19
7	*324*	*324*	326	326	331	337	341	341	339	332	326	*324*	331	17
6	*319*	*319*	321	322	327	331	336	335	333	328	321	321	326	17
5	315	*314*	318	319	322	326	331	329	325	323	317	317	321	17
4	*310*	*310*	314	314	319	321	325	323	320	318	311	314	317	15
3	306	*303*	309	311	317	318	318	317	315	312	306	309	312	15
2·5	302	*301*	308	310	317	317	315	314	313	310	303	306	310	16
2	*300*	*300*	306	309	317	316	312	312	311	309	301	303	308	17
1·5	*297*	298	305	308	316	316	309	309	309	308	299	300	306	19
1	*295*	297	304	308	315	315	306	308	308	307	297	297	305	20
0·5	*293*	296	303	306	314	314	304	306	305	306	295	295	303	21
Surface (0·17)	*291*	292	303	304	311	313	303	304	302	302	294	294	301	22

The values for each flight were obtained graphically according to the method described by Sir N. Shaw.[1]

Up to 12 gkm. the minimum mean monthly potential temperatures occur *generally* in January, but at some heights are shifted to December or February. This may be due to the smallness in the number of observations. Up to 3 gkm., the maximum occurs in May-June, and between 4 and 13 gkm. either in July or August.[2] The character of the annual variation undergoes a reversal above 13 gkm., the minimum occurring above that level in August and the maximum in one of the months December, January or February. The smallest annual variation is at 13 gkm.

[1] *Q. J. R. Met. Soc.*, 51, 1925, p. 216.

[2] If we consider the moisture contained in the atmosphere also, the part of the year when the lower layers have maximum heat energy per unit volume i July and August.

The general nature of the curves of annual variation of potential temperature (fig. 4) bears a striking resemblance to the idealised potential temperature curves of cyclones and anti-cyclones represented in Sir N. Shaw's Manual of Meteorology, Vol. II, p. 118, the monsoon season July and August corresponding to anti-cyclones and the winter to cyclones. The height at which the difference between the potential temperatures of cyclones and anti-cyclones becomes a minimum in European latitudes is 9 km., which may be compared with the height (13 gkm.) of minimum seasonal variation of potential temperature over north India.

8. MONTHLY MEAN TEMPERATURE-ENTROPY, PRESSURE-DEW-POINT AND WIND DIAGRAMS.

The monthly mean temperature-entropy and pressure-dew-point graphs are drawn in figures 5(*a*) to (*l*). The north and east components of monthly mean winds over Agra obtained from the daily pilot balloon ascents of the period 1914-25 are also drawn in the same figures. In spite of the fact that the temperature-humidity and wind-diagrams refer to different periods and the former are very limited in number, the combination serves to give one a more complete picture of the structure of the atmosphere over Agra in different seasons. It is hoped to discuss a few selected individual tephigrams in a later paper.

Some general features of the curves may be briefly indicated :—

(1) In the period November to May, the atmosphere above 9 or 10 km. is more or less stable for rising saturated air. The rate of increase of the westerly component of velocity with height also diminishes at about this height. There is a small yet distinct northerly component of velocity up to at least 12 km.[1] With the progress of the hot season from the end of February to May there is a gradually increasing thickness of surface air up to 5 km. which is strongly unstable for rising saturated air and approaches instability even for dry air. It is well-known that the frequency of dust-storms also increases similarly. Conditions in June are similar to those in May in the first 4 km. but the moisture-content is greater above that level and between 4 and 13 km., the tephigram follows approximately the curve of saturation adiabatic. Above 13 km. the atmosphere becomes stable.

(2) In July and August, there is a close approach to labile equilibrium for rising saturated air from $2\frac{1}{2}$ to 14 km. These limits are slightly contracted in September and the stability also is somewhat greater above 5 km. It will be noticed that in these three months, if an adequate supply of moist air could be introduced at or below 2 km., instability extending practically throughout the troposphere would result ; actually, all fresh advances of monsoon into the United Provinces introduce moist air in these layers and are accompanied by thunderstorms.

(3) In October the atmosphere is definitely stable above 7 km. ; below that level it is unstable for rising saturated air but the chances of supply of moisture at lower level become so small that instability is rarely reached.

[1] It is possible that in the higher layers, this is a characteristic peculiar to days on which high pilot balloon flights were possible.

9. THE STRATOSPHERE OVER AGRA AND ITS SEASONAL VARIATIONS.

For classifying the nature of the transition from the troposphere to the stratosphere and defining the height of the tropopause H_c, similar conventions as those in use in the London Meteorological Office were adopted. They are :—

Type I.—When the stratosphere commences with an inversion, H_c is the height of the first point of zero lapse-rate.

Type II.—When the stratosphere begins with an abrupt transition to a lapse-rate below 2° per kilometre without inversion, H_c is the height of the abrupt transition.

Type III.—When the change of lapserate is gradual, the base of the stratosphere is taken at the point where the mean fall of temperature for the kilometre next above is 2° or less, provided it does not exceed 2° per kilometre for any subsequent kilometre.

Type IV.—A fourth composite type with an inversion above a transition of type II or III is often met with between November and April. In the latter case, however, the last proviso is not always strictly satisfied ; immediately below the inversion corresponding to type I, there is often a thin layer with lapse-rate exceeding 2°C/gkm.

When the transition occurs in two stages two values of H_c and T_c are given, one corresponding to each stage. Photographs of two records showing tropopause of type IV are shown in figure 6 (a) and (b).

From the point of view of seasonal variation of the type, height and temperature of the tropopause over Agra, the year may be divided broadly into two parts :—

(1) *Middle of May to end of October.*

During this period, the type of tropopause is either I or II ; if II, the initial sudden change of lapse-rate is followed by an inversion soon after, so that there is always an inversion of temperature in the stratosphere. The mean value of H_c is 16·5 gkm. and of T_c 194°·5 A.

(2) *November to middle of May.*

In this period, types III and IV are more frequent. There is almost always an inversion of temperature above 17 gkm. The mean values of H_c and T_c during this period are 16·2 gkm. and 201°A if we take the values corresponding to the higher value of H_c on occasions when transitions were of type IV and 14·9 gkm. and 203°·5 if we take values corresponding to the lower values of H_c.

The individual values of the heights and temperatures of the tropopause are plotted against the dates of the ascents in figures 7(*a*) and (*b*). When the transition is of type IV, values corresponding to both positions of change of lapse-rate are plotted. The smoothed monthly mean values of H_c and T_c are given in table 15.

Table 15.

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
H_c gkm.	15·2	15·4	16·1	16·3	16·4	16·4	16·4	16·4	16·4	16·2	15·5	15·0
T_c°A	203	203	203	203	201	196	194	193	193	194	200	203

A remarkably sudden fall of the height of the tropopause and a rise in its temperature occur between October and November. This takes place more or less simultaneously with the setting in of winter conditions over North India and more than a month and a half later than the time of withdrawal of the monsoon. The high levels and low temperatures of tropopause over Agra between the months May and October may be due to two causes :—

(1) strong convective action in the higher layers of the troposphere, and

(2) advective movement of air in the higher layers of the troposphere from lower latitudes or from regions where convection is vigorous.

It is very probable that during July and August when the monsoon is vigorous over the United Provinces, and the prevalent wind direction at the cirrus level is from Bengal and Assam where rainfall is particularly heavy, both (1) and (2) are important causes. To a smaller extent, this is also true for June and September. To account for the high position of the tropopause in May and October, we have to fall back on (2) alone. It is known that the air movement over Agra in the months May to October has a small yet distinct southerly component above 6 or 7 km. up to the cirrus level and possibly also up to the tropopause. In Europe, the maximum height of the tropopause occurs in October and Gold[1] connects this with the incoming of air at and near the cirrus level from lower latitudes. In Canada[2] also the maximum value of H_c occurs in the period July-September.

It is of interest to note that the annual variation of H_c and T_c over Batavia is complementary to that over Agra. In figures 8(*a*) and (*b*), diagrams similar to 7(*a*) and (*b*), have been drawn for Batavia. The annual variation of H_c at Batavia is not so conspicuous as at Agra, but that of T_c is quite marked.

The minimum values of T_c occur during December and January over Batavia.

Values of T_c are plotted against the corresponding values of H_c in figure 9. The values for the Batavian ascents from 1910 to 1915[3], for the English ascents in 1924[4], and for Canadian ascents in 1914 and 1915[5] are also plotted for comparison. It is well-known that over European latitudes, a rise of the tropopause is generally accompanied by a fall of its temperature ; this is also true for Agra in winter and early hot season, but over Batavia throughout the year and over Agra in the monsoon the tropopause does not show any tendency to rise above 17·5 gkm. in spite of decreasing temperature. (The single point at 18·6 gkm. observed over Batavia on 2nd October 1912 appears to be exceptional). It is also known that in general, the lower the temperature of the tropopause, the stronger is the inversion in the first few kilometres of the stratosphere[6]. There must therefore be a strong force resisting the further raising of the tropopause.

In this connection, it may be noted that over Agra high temperature in the neighbourhood of 10 gkm. is associated with a large fall of temperature in the next few kilometres above. The effect is mainly seasonal, but not entirely so. The coefficient of cor-

[1] *Geoph. Mem.*, No. 5, London M. O.

[2] *Upper Air Investigation in Canada*, (published by the Canadian Meteorological Service), p. 19, 1915.

[3] W. van Bemmelen, *Kon. Mag. et Met. Observ. te Batavia*, Verhandelingen No. 4.

[4] *The Observatories Year Book, 1924*, M. O. London.

[5] Loc. Cit.

[6] P. R. K. Rao, Distribution of temperature in the lower stratosphere, *Ind. Met. Dept. Scientific Notes*, Vol. I, No. 10.

relation between T_{10}, the temperature at 10 gkm. and $T_{10}—T_{16}$ the fall of temperature between 10 and 16 gkm. is 0·93 with a probable error of 0·02. Apparently the low temperature of T_c over tropical regions is therefore mainly of tropospheric origin.

10. UPPER AIR TEMPERATURES AND ENTROPIES OVER THE NORTHERN HEMISPHERE IN SUMMER AND WINTER.

It is of interest to compare upper air temperatures over Agra with those over other countries. In figure 10, winter temperatures over Agra are compared with summer and winter temperatures over Europe[1] and in figure 11 monsoon temperatures over Agra with summer and winter temperatures over Batavia. In the latter figure, the curves of saturation adiabatic corresponding to surface temperatures 295° and 305°A have also been drawn. The small difference between the summer and winter temperatures over Batavia and the close parallelism of these curves and of the Agra monsoon curve to the curve of saturation adiabatic are noteworthy features. At all levels below 13 gkm, Agra shows during the monsoon higher temperatures than Batavia in summer.

Sir Napier Shaw, in his " Manual of Meteorology ", Vol. II, p. 100, has given a diagram showing the variation with latitude of upper air temperatures over the northern hemisphere in summer and winter. In figure 12,[2] that diagram has been amplified by the inclusion of Agra data and data over other places up to 25 gkm. as far as they are available. Some of the prominent features of the diagram may be briefly summarised :—

(1) The coldest air over the earth which is at a temperature of about 190°A lies at a height of about 17 gkm. over the equator in the form of a flat ring surrounded by rings of warmer air.[3] It is displaced towards higher latitudes in summer.[4]

(2) In the lower layers of the stratosphere, over tropical and sub-tropical regions, temperature definitely increases with height. The Agra and Batavia results indicate a temperature of about 220°A and the American results about 230°A at a height of 24 km.

(3) In the northern summer, the region of highest temperatures in the troposphere is shifted to 20—40°N, the region of sub-tropical anticyclones (*vide* isobars at 8 km. in Sir Napier Shaw's Meteorology, Vol. II, p. 262.) There is, however, the possibility that Agra temperatures are exceptionally high during the monsoon and exaggerate the high temperatures over this region.

(4) The height of the tropopause is more or less constant from the equator to about 30°N during northern summer and has a steep downward slope towards the north between 30° and 50° in summer and between 25° to 45° in winter. The curve of variation of H_c with latitude has the same general characteristics as that deduced by V. Bjerknes[5] from upper winds.

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[1] W. H. Dines, Characteristics of the Free Atmosphere, *Geoph. Mem.* No. 13.

[2] First published in *Nature*, June 1, 1929, p. 923.

[3] The possibility of this was pointed out by V. Bjerknes in his paper " On the Dynamics of the Circular Vortex, etc." *Geofys. Publ.* Vol. II, No. 4, p. 90.

[4] It is interesting to note that over Batavia in July, the easterly component of wind is a maximum (16 m.p.s.) at a height of about 14 gkm. and changes rapidly to a westerly of 5 m.p.s. at 19 km. (Sir N. Shaw, Meteorology, Vol. II, p. 272). If the law of geostrophic balance hold at these latitudes, this would require a temperature gradient with temperature decreasing towards the south between these levels and a corresponding modification of figure 12.

[5] Loc. Cit. Fig. 21, p. 65.

A diagram showing the distribution of potential temperature over the northern hemisphere in summer and winter (modified from that given on page 116 of Sir N. Shaw's Meteorology, Vol. II) is given in figure 13.[1] The potential temperatures plotted are temperatures in degrees absolute which the air at any place would assume if compressed or expanded adiabatically to 1,000 mb. Since the potential temperature θ and entropy φ of dry air are connected by the relation

$$\varphi = C_p \log \theta + \text{constant.}$$

where c_p is the specific heat of dry air at constant pressure, lines of equal potential temperature are also lines of equal entropy. For convenience, isentropics for values of entropy 10×10^6 to 18×10^6 C. G. S. units in steps of 10^6 units have also been drawn, entropies being measured from a zero at 100°A and 1000 mb.[2]

It is possible that the trough of high entropy near 25°N will become less marked when more data from similar latitudes in other parts of the world are available. Over the inter-tropical belt, the values of entropy are markedly high below about 10 gkm. and low between 12 and 20 gkm. with a pronounced concentration of isentropics between 17 and 20 gkm. The analogy of this diagram of zonal distribution of entropy to that of seasonal variation of entropy over Agra is very striking.

It is hoped to discuss in a later paper the relationship between the general circulation of the atmosphere and the distribution of temperature and entropy with special reference to the Indian monsoon region.

In conclusion, I wish to express my indebtedness to Mr. G. Chatterjee for his valuable co-operation and help. My thanks are also due to Mr. K. P. Ramakrishnan for substantial assistance in the tabulation and arrangement of data.

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[1] In addition to the data used in preparing fig. 12, some data obtained from sounding balloon ascents at Poona during the winter of 1928-29 have also been utilised.

[2] Sir N. Shaw. 'Tables for calculating the entropy of air'. Report of the Meeting of the International Commission for the exploration of the Upper Air, Leipzig, 1927, p. 51 *et seq.*

APPENDIX A.

Number of sounding balloons recovered from among those let off from Agra and their places of fall.

The number of balloons sent up during each month and the number recovered out of them are shown in Table 16.

Figure 14 shows the distances and bearings of places of fall of all meteorographs which were sent up from Agra during the period under discussion and which reached heights exceeding 10 gkm. The places of fall of instruments sent up during the periods March to May, June to 15th October and 16th October to February are indicated by separate marks. The number underneath each mark and Table 17 serve to identify the date of ascent of the meteorograph and the height reached. The diagram shows in a rough way the annual variation of upper winds over Agra. The horizontal distances travelled by the balloons are longest during the winter and shortest during the monsoon. Easterly currents of any considerable thickness are only met with in the latter season. Even then, the currents are generally weak. During winter and hot season, the direction of place of descent is generally towards the east with some scatter to north and south depending on the weather situation at the time of ascent.

Table 16.—Number of balloons sent up (n_1) and number recovered out of them (n_2).

	Jan.		Feb.		Mar.		Apl.		May.		June.		July.		Aug.		Sep.		Oct.		Nov.		Dec.	
Year.	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2
1925 .	..	..	..	..	..	..	..	..	..	..	..	..	8	4	6	3	3	3	1	1	..	..	..	..
1926 .	6	3	..	..	6	2	6	6	8	2	7	5	6	3	6	4	6	4	6	3	5	4	7	1
1927 .	3	2	5	3	2	2	5	4	5	3	11	6	6	2	7	4	6	3	15	12	8	5	7	4
1928 .	6	4	8	4	10	7	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Total .	15	9	13	7	18	11	11	10	13	5	18	11	20	9	19	11	15	10	22	16	13	9	14	5

TABLE 17.—DISTANCES AND DIRECTIONS OF PLACES OF FALL OF THE BALLOONS.

(*N.B.*—Those that did not reach a height of 10 gkm. have been excluded.)

No. in diagram.	Date of ascent.	Maximum height reached. Gkm.	Distance of place of fall. Km.	Direction of place of fall degrees from N.	No. in diagram.	Date of ascent.	Maximum height reached. Gkm.	Distance of place of fall. Km.	Direction of place of fall degrees from N.
2	18-8-25	10·2	163	80	53	11-6-27	19·0	122	70
3	21-8-25	10·9	39	280	55	14-6-27	23·2	45	45
7	15-10-25	11·4	410	100	56	15-6-27	18·2	82	70
13	8-4-26	23·0	116	80	57	16-6-27	18·7	29	0
14	10-4-26	19·1	328	110	58	6-7-27	13·6	29	0
16	16-4-26	19·7	314	95	59	12-8-27	18·0	48	315
17	29-4-26	19·5	203	85	60	26-8-27	12·5	29	0
18	4-5-26	17·6	122	70	61	29-8-27	14·9	62	295
19	27-5-26	19·3	122	70	62	13-9-27	16·4	40	70
20	10-6-26	17·8	109	85	63	17-9-27	18·8	25	45
21	11-6-26	18·3	109	85	64	22-9-27	19·0	47	90
22	14-6-26	10·5	167	160	65	1-10-27	18·7	122	70
23	22-6-26	11·3	113	110	67	14-10-27	18·8	122	70
24	30-6-26	17·5	69	30	68	17-10-27	18·6	123	110
29	27-8-26	15·8	48	280	69	18-10-27	12·4	132	110
32	16-9-26	11·2	135	350	70	19-10-27	13·9	139	110
34	2-10-26	18·5	156	75	71	21-10-27	12·1	113	115
35	10-10-26	19·3	106	125	73	31-10-27	15·4	204	95
36	12-11-26	10·6	116	80	74	10-11-27	20·3	356	85
37	15-11-26	17·7	317	85	76	14-11-27	12·1	231	65
38	24-11-26	19·6	317	85	77	28-11-27	20·9	216	90
39	25-11-26	18·5	359	80	78	9-12-27	18·0	315	90
40	8-12-26	19·0	301	70	79	14-12-27	15·9	216	90
41	6-1-27	18·8	385	90	80	29-12-27	13·7	282	75
42	12-1-27	11·8	338	120	81	6-1-28	16·9	386	90
43	16-2-27	18·7	410	105	82	14-1-28	14·9	356	85
44	17-2-27	21·6	385	90	83	25-1-28	20·2	386	90
45	15-3-27	17·7	356	85	84	26-1-28	18·3	519	95
46	25-3-27	19·1	241	110	88	24-2-28	18·9	222	140
47	9-4-27	20·4	278	90	89	8-3-28	14·1	250	80
48	22-4-27	19·5	246	90	90	16-3-28	20·7	252	85
49	24-4-27	14·2	140	90	91	20-3-28	18·4	245	90
50	12-5-27	14·5	218	90	92	23-3-28	18·6	250	80
51	19-5-27	19·9	173	25	93	27-3-28	16·1	280	90
52	23-5-27	20·3	110	90	94	31-3-28	12·1	160	85

APPENDIX B.

TABLE 18.—MEAN MONTHLY PRESSURES AT DIFFERENT GEOMETRIC HEIGHTS OVER AGRA. (mb.).

Height in km.	Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	54	54	55	56	56	..	..	..	..	..	55	..
19	64	65	65	66	68	68	..	..	67	67	65	65
18	75	76	77	77	79	80	..	80	79	78	76	76
17	89	91	92	92	94	95	..	96	95	94	90	92
16	106	107	109	109	112	114	..	114	113	112	107	108
15	124	126	129	128	131	134	..	136	135	133	126	127
14	147	148	152	151	156	158	158	160	159	157	150	150
13	173	173	178	177	182	185	187	187	186	182	176	174
12	203	203	208	207	212	216	218	218	216	213	206	204
11	237	237	243	242	246	250	252	252	252	248	241	240
10	275	275	281	281	286	288	291	290	290	286	280	279
9	318	317	322	322	329	330	332	333	332	328	320	321
8	365	365	370	370	376	377	378	379	379	376	368	370
7	421	420	424	425	430	430	431	432	433	430	422	424
6	482	479	487	486	491	490	490	492	493	490	483	487
5	550	547	553	553	557	556	555	556	557	556	550	554
4	622	620	627	627	631	627	625	627	628	629	624	627
3	707	705	709	708	712	708	705	707	709	711	707	710
2	799	797	801	800	801	796	794	797	799	803	800	802
1	901	898	900	897	897	892	891	894	896	901	901	903
Surface (0·17)	994	991	989	985	982	977	979	980	984	989	993	995

TABLE 19.—MEAN MONTHLY TEMPERATURES AT DIFFERENT GEOMETRIC HEIGHTS OVER AGRA (°A).

Height in km.	Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	214	215	200	210	207	..	..	..	..	..	207	..
19	206	211	203	205	201	203	..	..	..	202	205	205
18	203	207	202	204	198	200	..	199	199	195	204	201
17	203	205	201	203	200	197	..	194	195	193	203	201
16	203	205	203	203	204	200	..	197	201	197	203	204
15	205	207	207	207	209	206	205	205	205	203	205	209
14	209	211	212	212	214	213	213	212	212	210	208	211
13	213	217	219	216	219	220	222	222	221	218	213	212
12	219	224	225	221	226	228	232	232	229	225	221	217
11	224	229	230	227	233	237	241	240	238	233	228	222
10	229	234	236	233	240	245	249	247	245	240	235	230
9	238	238	241	240	246	252	255	256	253	247	242	238
8	245	245	247	247	253	258	261	261	260	253	247	245
7	251	252	254	254	259	264	267	267	265	260	253	253
6	258	257	261	261	265	269	273	272	270	266	260	260
5	264	264	267	268	272	275	278	277	274	272	266	267
4	270	269	274	274	279	281	283	282	279	277	271	274
3	276	273	280	282	287	287	287	287	285	282	277	279
2	281	281	287	290	297	296	292	292	291	289	282	284
1	287	288	295	298	306	305	296	298	298	298	288	287
Surface (0·17)	291	293	301	303	309	311	301	303	301	301	293	293

TABLE 20.—MEAN MONTHLY DENSITIES AT DIFFERENT GEOMETRIC HEIGHTS OVER AGRA.
(Gms. per C. metre.)

Height in km.	Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean.
20	92	91	98	96	96	97	..	..	..	..	95	..	95
19	109	109	114	120	118	119	..	..	..	118	112	113	115
18	132	134	138	137	143	145	..	147	146	146	133	139	140
17	155	157	163	160	167	170	..	176	173	173	156	162	165
16	183	183	188	189	193	200	..	203	201	201	186	185	192
15	213	214	220	217	222	230	..	232	231	229	216	214	222
14	247	247	251	249	255	261	262	263	263	262	254	247	255
13	283	281	285	286	290	295	296	296	295	292	288	286	289
12	324	318	324	328	329	332	329	329	331	331	328	329	328
11	369	361	368	369	369	369	365	367	369	369	366	375	369
10	417	405	413	418	414	411	407	408	412	413	412	421	412
9	468	466	466	468	467	467	452	454	458	464	461	472	464
8	523	526	523	523	519	509	504	505	507	518	519	526	517
7	585	582	584	585	580	569	562	563	568	576	581	587	577
6	651	648	649	648	644	633	622	626	631	640	646	652	641
5	724	721	720	719	712	703	692	695	705	711	719	724	712
4	802	800	795	795	785	775	763	770	778	787	800	795	788
3	890	896	879	873	860	853	849	853	863	875	887	884	872
2	988	973	967	957	935	929	937	942	947	962	983	979	958
1	1,092	1,081	1,057	1,049	1,020	1,011	1,036	1,032	1,037	1,048	1,085	1,087	1,053
Surface (0.17)	1,188	1,173	1,138	1,129	1,101	1,089	1,118	1,115	1,129	1,139	1,175	1,175	1,139

APPENDIX C.

Soundings with Registering Balloons, 1925.

AGRA LAT. 27° 10′ N. LONG. 78° 5′ E.

TABLE 21.—TEMPERATURE IS GIVEN IN DEGREES ABSOLUTE, PRESSURE IN MILLIBARS, HEIGHT IN GEODYNAMIC KILOMETRES, WIND VELOCITY IN METRES PER SECOND, WIND DIRECTION IN DEGREES FROM NORTH IN THE CLOCKWISE DIRECTION AND HUMIDITY AS PERCENTAGE. I. S. T.=INDIAN STANDARD TIME.

Date Time of ascent I. S. T.	July 22. 18 hrs. 47 m.	Aug. 18. 18 hrs. 53 m.	Aug. 21. 18 hrs. 42 m.	Sept. 5. 19 hrs. 21 m.	Sept. 23. 18 hrs. 55 m.	Sept. 24. 18 hrs. 42 m.	Oct. 15. 17 hrs. 45 m.
Pressure at M. S. L.	1,000	996	997	1,000	1,007	1,010	1,002
Wind (Anemograph)—							
Velocity	5·3	3·4	2·0	1·8	6·3	3·0	....
Direction	225	270	245	290	90	180	....
Humidity at Surface	92	55	58	65	47	74	42
Greatest height reached	6·2	10·2	10·9	13·6	5·5	5·0	11·4
Corresponding Temperature	273	244	242·5	217	267	269	232
Corresponding pressure	473	273	248	165	513	550	225
Place of fall	....	Sivorah Fatehabad	Lokaira Kairabh.	....	....	....	Sultanpur
Distance	....	163 km.	39 km.	....	....	....	410 km.
Bearing	....	80°	280°	....	....	....	102°

22nd July 1925.—Ci, A Cu, and N at ascent. Monsoon vigorous in the Gangetic plain and submontane Punjab and moderately active in Rajputana.
18th August 1925.—6 Ci at ascent. Monsoon weak in Rajputana and United Provinces.
21st August 1925.—6 Ci and 1 Cu at ascent. There was a storm in the Bay with centre south of the Sunderbans at 8 A.M. on the 21st. Next morning it lay as a depression over Chota Nagpur. The monsoon was weak over northwest India and the United Provinces.
5th September 1925.—Fine weather. A depression formed near Sandheads on the morning of the 6th and moved slowly in a northwesterly direction.
23rd September 1925.—Fine weather with some A Cu on the horizon. Western disturbance affecting the Punjab. Dust and thunderstorms were reported from the Punjab on the morning of the 24th.
24th September 1925.—8 A Cu at ascent. The disturbance had passed away on the morning of the 25th.
15th October 1925.—Clear weather. There was a depression near head of Bay. Northwest and Central India dry.

Soundings with Registering Balloons, 1925.

Agra Lat. 27° 10′ N. Long. 78° 05′ E.

TABLE 22.—T=TEMPERATURE IN DEGREES ABSOLUTE. P=PRESSURE IN MILLIBARS. H=LEVEL IN GEODYNAMIC KILOMETRES, R.H.=RELATIVE HUMIDITY. G.L.=GROUND LEVEL. M.S.L.=MEAN SEA LEVEL. AND I.S.T.=INDIAN STANDARD TIME.

Date	July 22.	August 18.	August 21.	Sept. 5.	Sept. 23.	Sept. 24.	Oct. 15.	Date.
Time of Ascent I. S. T.	18 hrs. 47 m.	18 hrs. 53 m.	18 hrs. 42 m.	19 hrs. 21 m.	18 hrs. 55 m.	18 hrs. 42 m.	17 hrs. 45 m.	Time of Ascent I. S. T.

PRESSURE, TEMPERATURE AND HUMIDITY AT GIVEN HEIGHTS.

H.	P	T	R.H.	P	T	R.H.	P	T	R.H.	P	T	R.H.	P	T	R.H.	P	T	R.H.	P	T	R.H.	H.
20·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	20·0
19·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	19·0
18·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	18·0
17·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	17·0
16·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	16·0
15·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	15·0
14·0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	14·0
13·0	..	..	..	..	..	..	..	..	..	181	222	..	..	..	..	..	..	..	..	..	..	13·0
12·0	..	..	..	..	..	..	..	..	..	212	30	..	..	..	..	..	..	..	..	..	..	12·0
11·0	..	..	..	..	..	..	..	..	..	246	39	..	..	..	..	..	..	..	238	235	6	11·0
10·0	..	..	..	282	246·5	52	280	248·5	56	284	48	..	..	..	..	..	..	..	277	42	4	10·0
9·0	..	..	..	324	54	52	324	56	51	326	56	..	..	..	..	..	..	..	319	49·5	5	9·0
8·0	..	..	..	370	61·5	55	372	63	50	373	62·5	..	..	..	..	..	..	..	366	54·5	4	8·0
7·0	..	..	..	423	65	72	424	68	31	423	68	0	..	..	..	..	..	..	419	57	4	7·0
6·0	484	213·5	86	483	70·5	58	480	72·5	14	483	72·5	18	..	..	..	..	..	..	477	63	5	6·0
5·0	549	79·5	77	547	78·5	18	545	78·5	6	550	74	47	550	270·5	52	549	269	110	545	67	9	5·0
4·0	619	84	92	621	81	30	618	80	8	622	79·5	71	623	75·5	71	623	74·5	91	619	76	12	4·0
3·0	700	87·5	93	702	86	70	700	86	95	702	84·5	80	706	81	80	707	82	70	701	84·5	15	3·0
2·5	743	90	93	747	89	92	743	88·5	104	747	88	74	750	85	79	751	84·5	69	748	88	21	2·5
2·0	789	91·5	95	790	92	78	790	92	80	792	92·5	56	798	90	73	799	88·5	75	794	92·5	25	2·0
1·5	838	93	97	838	96·5	*52	837	96·5	63	840	96·5	*60	845	93·5	67	847	92·5	61	842	96	26	1·5
1·5	889	†94·5	96	888	301	*43	888	300 *	57	891	300·5	..	897	96·5	60	899	97	53	896	300	29	1·0
0·5	943	†97	94	942	*304	..	940	303·5*	..	945	302	*62	950	300	*60	952	98·5	59	947	303·5‡	..	0·5
*G.L. (0·17)	980	298	92	978	305·5	..	977	305·5	58	981	302·5	65	988	302·5	47	990	298	74	982	300·5	42	G.L. (0·17)
M.S.L.	997	..	..	995	..	..	994	..	..	998	.	..	1,005	..	..	1,008	..	..	999	..	..	M.S.L.

*Temperatures and humidities at G.L. are the values obtained at ascent, while at other heights the values are the means of those obtained from ascending and descending curves.
†Only one curve at these places.
‡ Extrapolated mean values.

Soundings with Registering Balloons, 1925.

AGRA LAT. 27° 10′ N. LONG. 78° 5′ E.

TABLE 23.—HEIGHTS IN GEODYNAMIC METRES AT WHICH CHANGES OF LAPSE-RATE OCCUR WITH CORRESPONDING PRESSURES IN MILLIBARS AND TEMPERATURES IN DEGREES ABSOLUTE.

Date.	Time of ascent. I. S. T.	H.	P.	T.	Remarks.
July 22 . . .	18 hrs. 47 m.	..	..	..	No sudden change of Lapserate anywhere.
August 18 . . .	18 hrs. 53 m.	2460	750	288·5	Gradual decrease of gradient.
		3900	630	281	Strong inversion.
		4270	600	283	
		5650	505	271	
		8000	370	261·5	
August 21 . . .	18 hrs. 42 m.	2550	740	288	Inversion.
		3400	665	282	Gradient decreases above this level.
		4100	610		Strong inversion in one curve.
		4400	585		
		4800	560	279·5	
		8700	340	260	Lapse-rate increases above this.
September 5 . . .	19 hrs. 21 m.	920	900	300·5	Gradual.
		4900	555	273·5	Nearly isothermal.
		5580	510	274	
		8900	330	256·5	
September 23 . .	18 hrs. 55 m.	3300	680	278·5	
September 24 . .	18 hrs. 42 m.	2200	780	287	
October 15 . . .	17 hrs. 45 m.	4980	547	267	Lapserate becomes smaller.
		7880	373	253	Strong inversion.

MGIPC—M—VIII-3-187—18-6-30—400.

SEASONAL VARIATION OF TEMPERATURE AT DIFFERENT HEIGHTS OVER AGRA
MONTHLY MEAN VALUES JULY 1925 TO MARCH 1928.

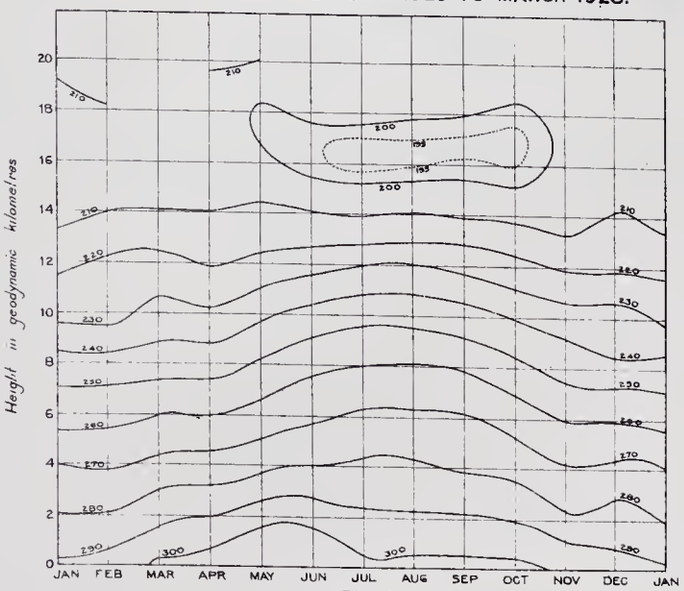
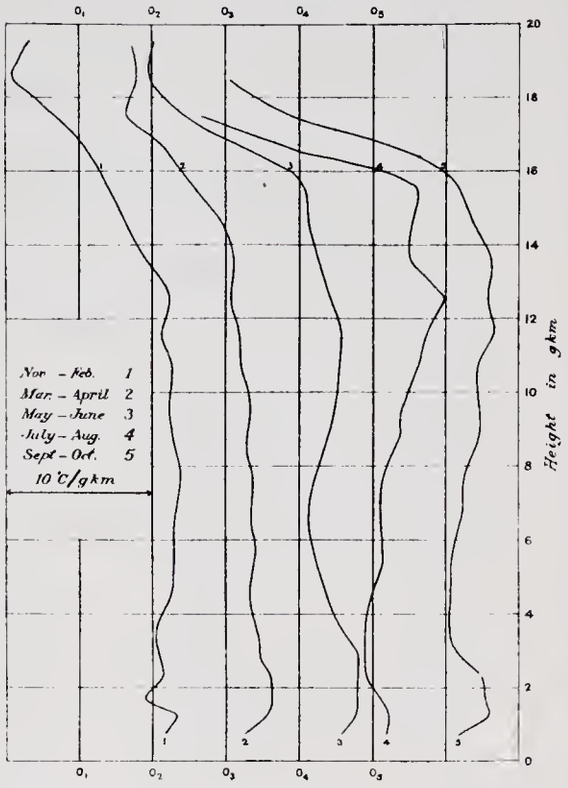


FIG. 1

VARIATION OF MEAN LAPSE-RATE WITH HEIGHT
IN DIFFERENT SEASONS



O_1O_1 is the line of zero lapse-rate for curve 1, O_2O_2 for curve 2 and so on

FIG. 2

MONTHLY MEAN PRESSURES AT DIFFERENT HEIGHTS OVER AGRA

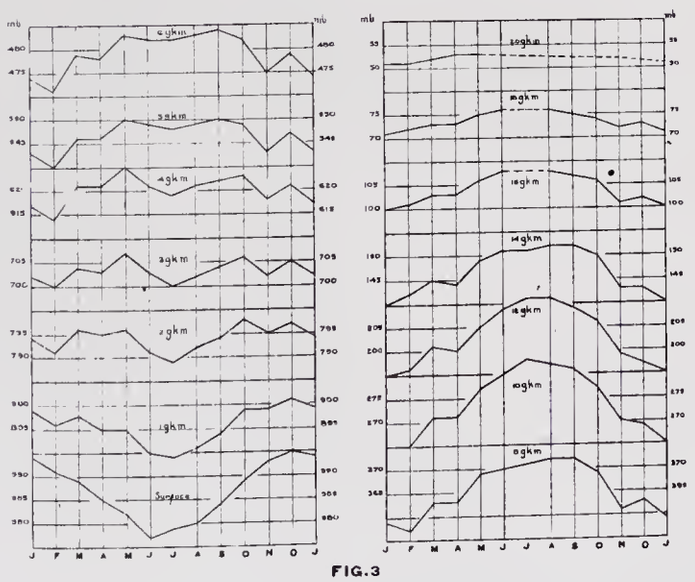


FIG.3

ANNUAL VARIATION
OF
POTENTIAL TEMPERATURE WITH HEIGHT
AGRA

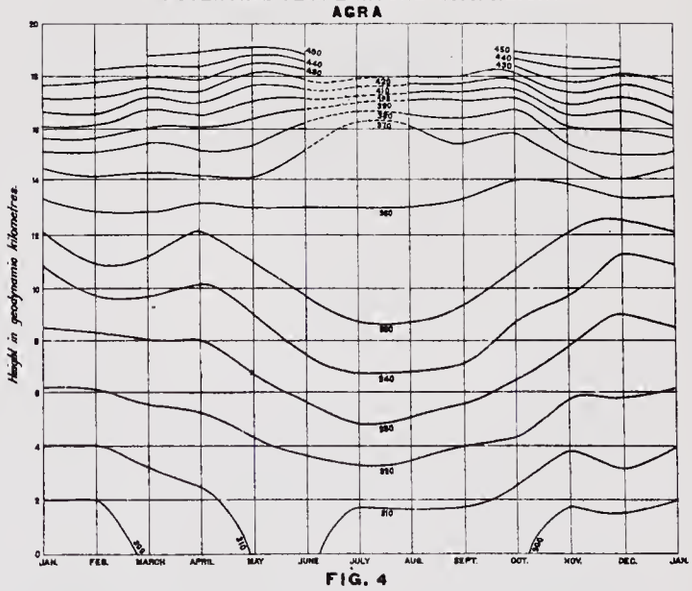


FIG. 4

G.P.I.O Poona, 1930.

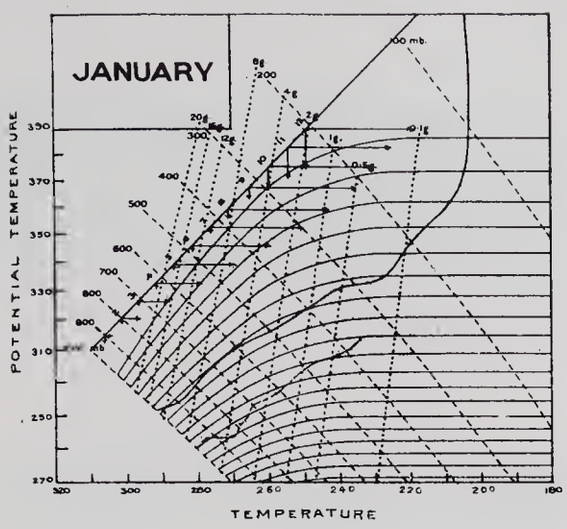


FIG. 5(a)

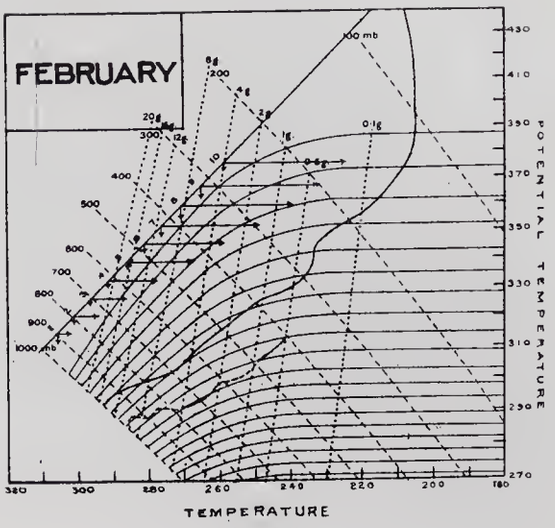


FIG. 5(b)

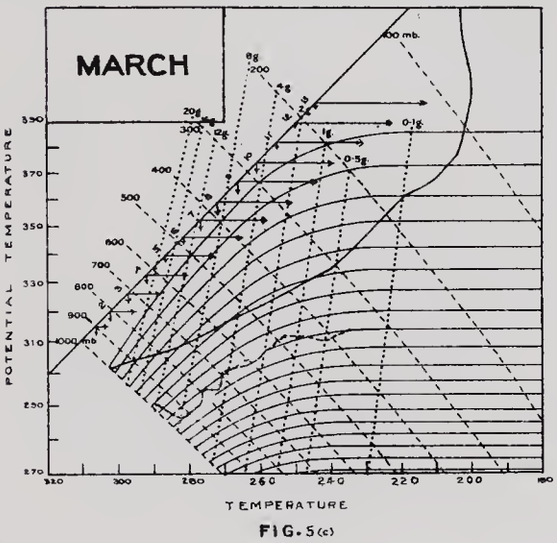


FIG. 5(c)

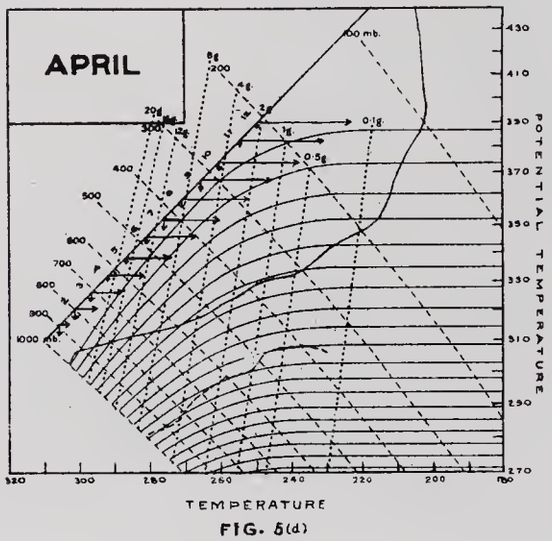


FIG. 5(d)

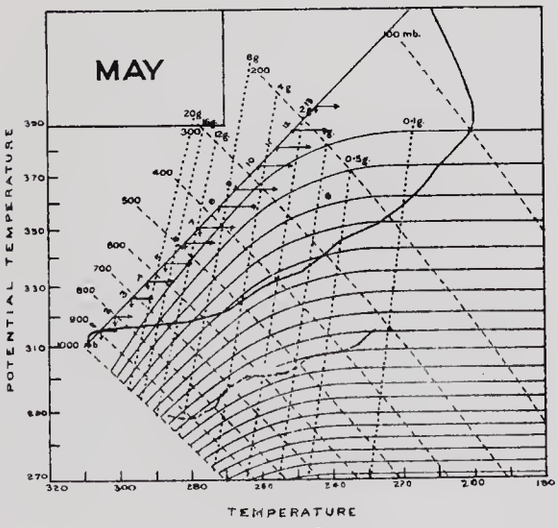


FIG. 5(e)

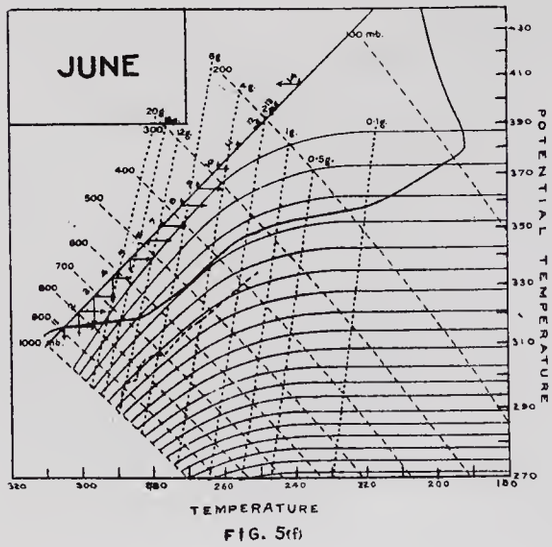


FIG. 5(f)

G. P. Z. O. Poona, 1930.

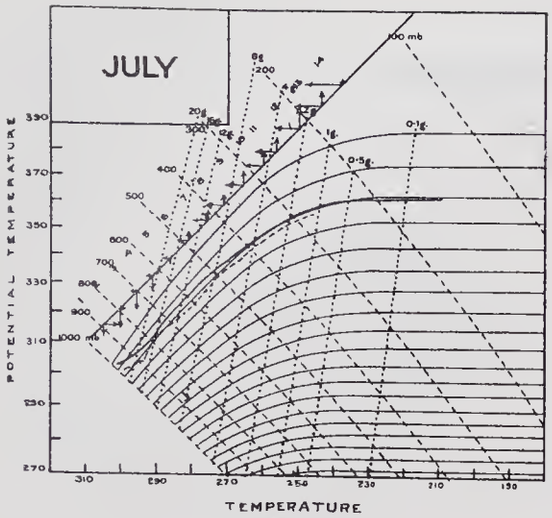


FIG. 5(g)

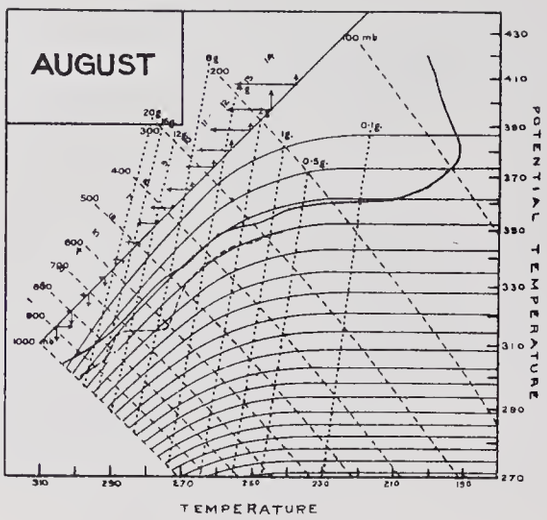


FIG. 5(h)

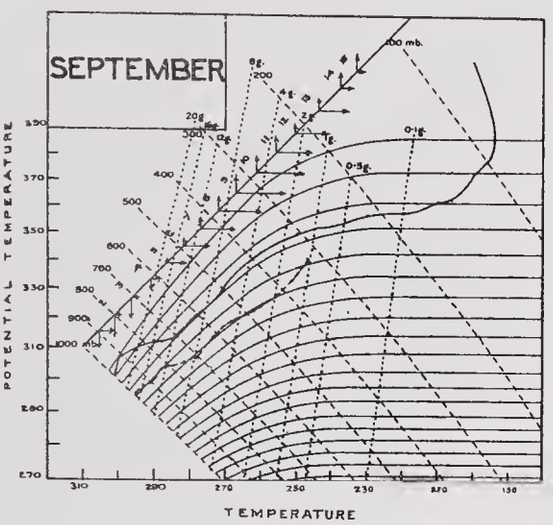


FIG. 5(i)

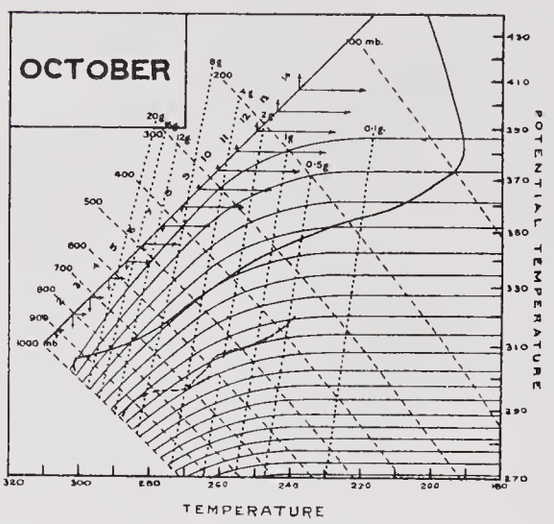


FIG. 5(j)

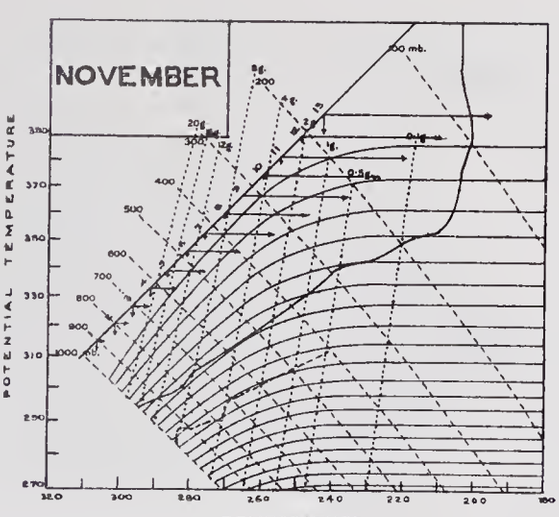


FIG. 5(k)

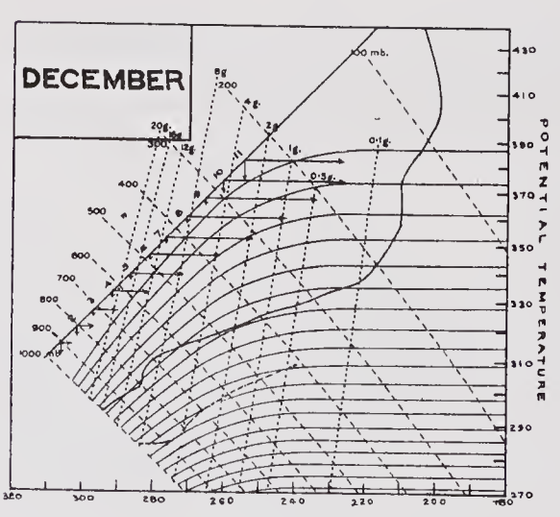


FIG. 5(l)

G.P.Z.O. Poona, 1930

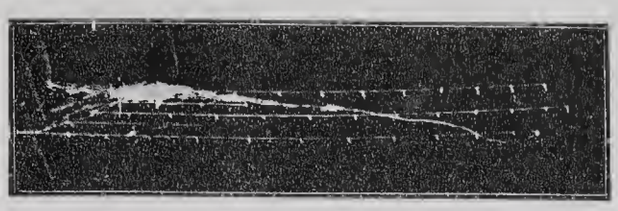


Fig. 6 (a) 10-11-27.

Fig. 6 (b) 28-11-27.

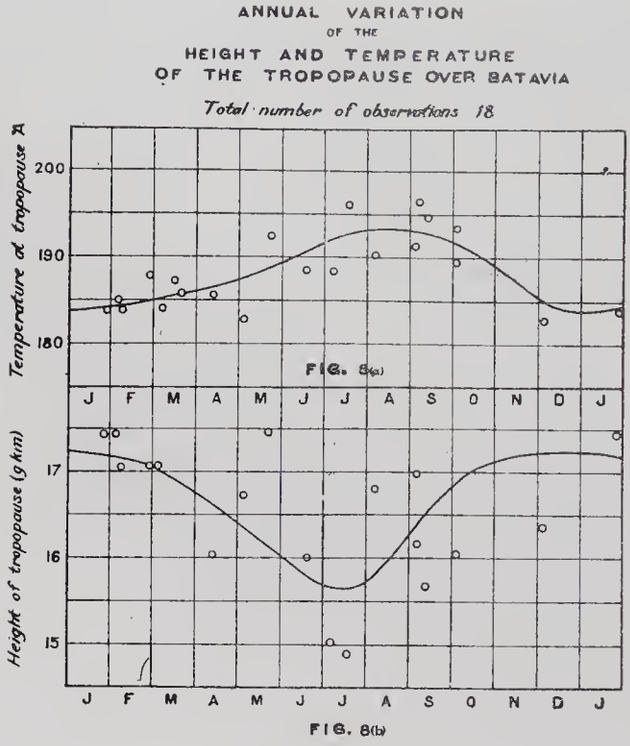


FIG. 8(b)

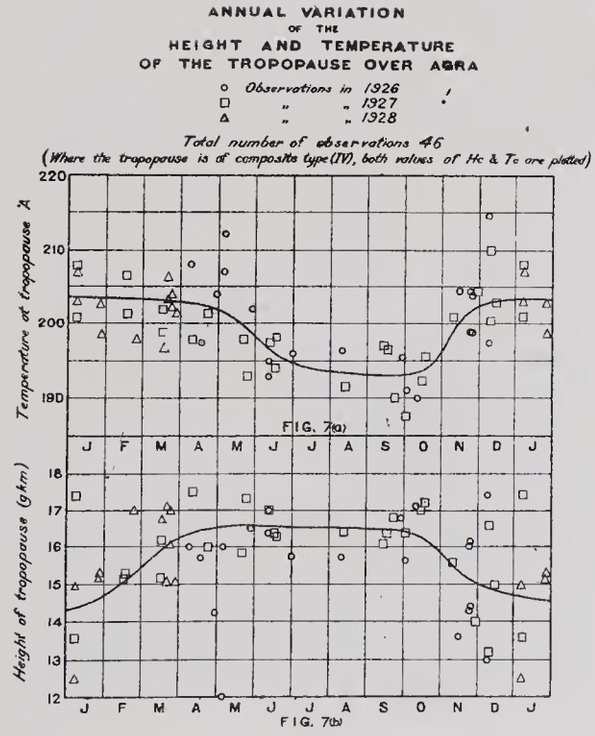


FIG. 7(b)

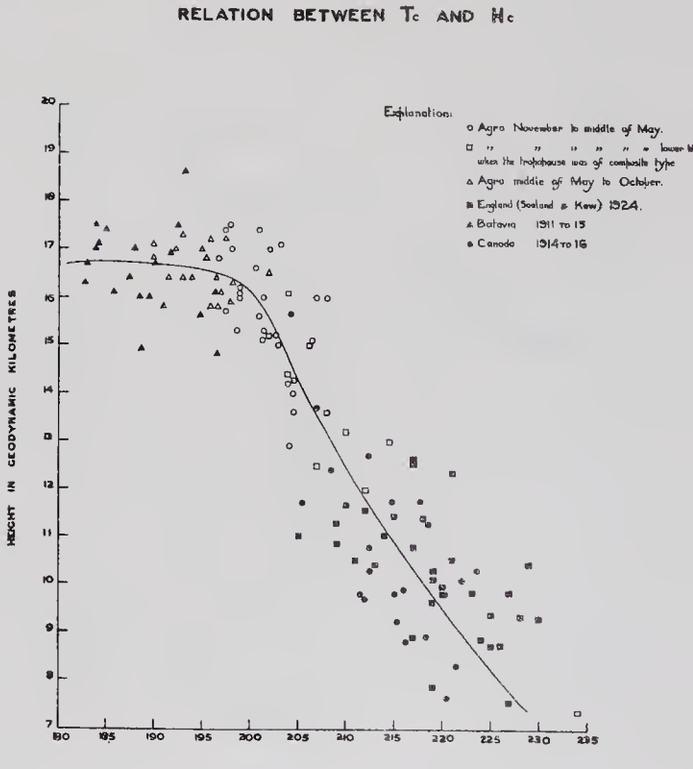


FIG. 9

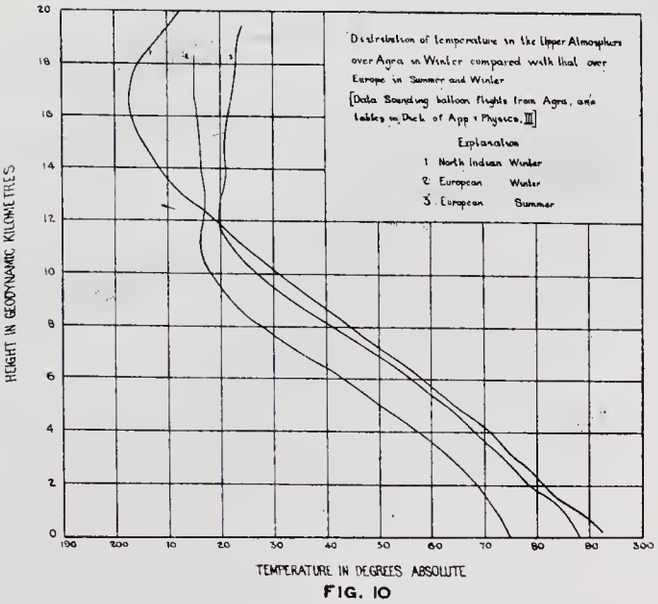

Distribution of temperature in the Upper Atmosphere over Agra in Winter compared with that over Europe in Summer and Winter
[Data Sounding balloon flights from Agra, and tables in Dict. of App. Physics. III]
Explanation
1. North Indian Winter
2. European Winter
3. European Summer
HEIGHT IN GEODYNAMIC KILOMETRES
TEMPERATURE IN DEGREES ABSOLUTE

FIG. 10

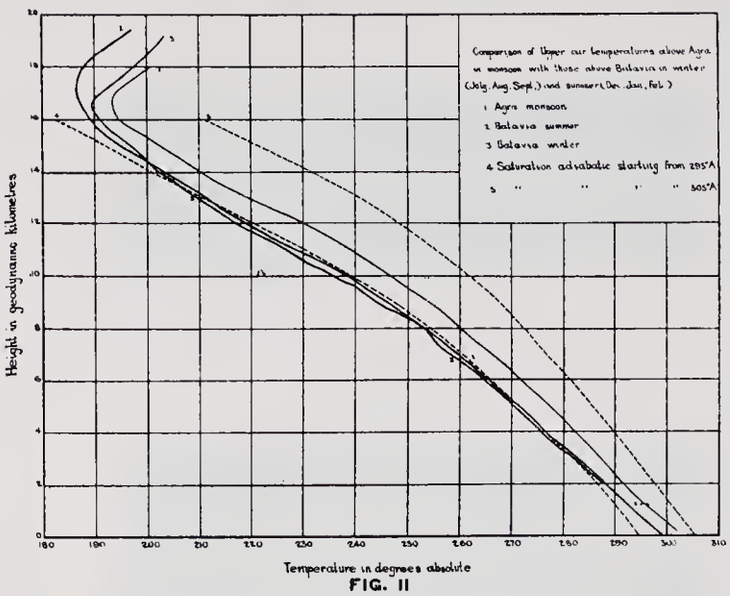

Comparison of Upper air temperatures above Agra in monsoon with those above Batavia in winter (July, Aug, Sept.) and summer (Dec. Jan, Feb.)
1. Agra monsoon
2. Batavia summer
3. Batavia winter
4. Saturation adiabatic starting from 295°A
Height in geodynamic kilometres
Temperature in degrees absolute

FIG. 11

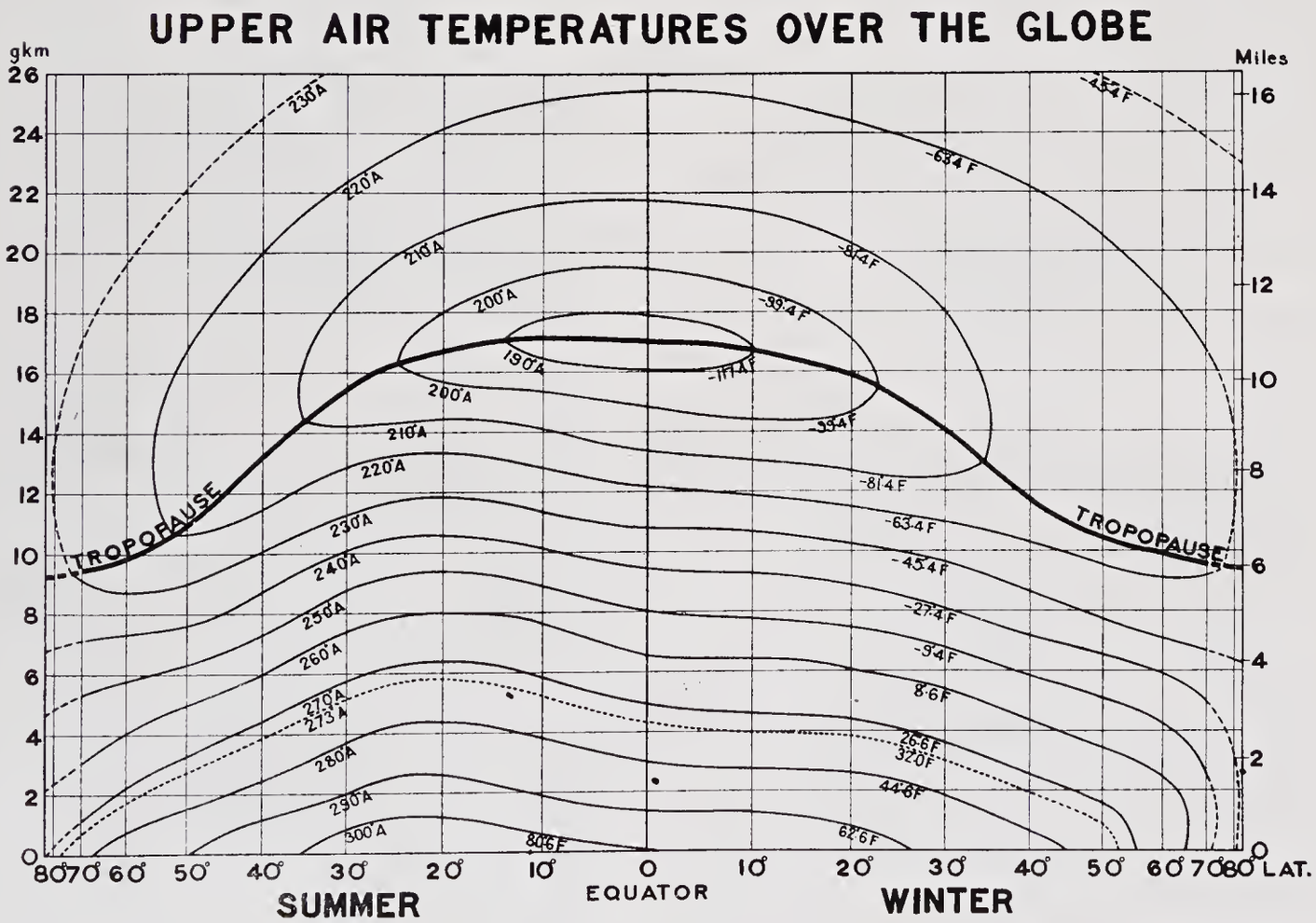


FIG. 12

G.P.Z.O. Poona, 1930.

UPPER AIR POTENTIAL TEMPERATURES OVER THE NORTHERN HEMISPHERE

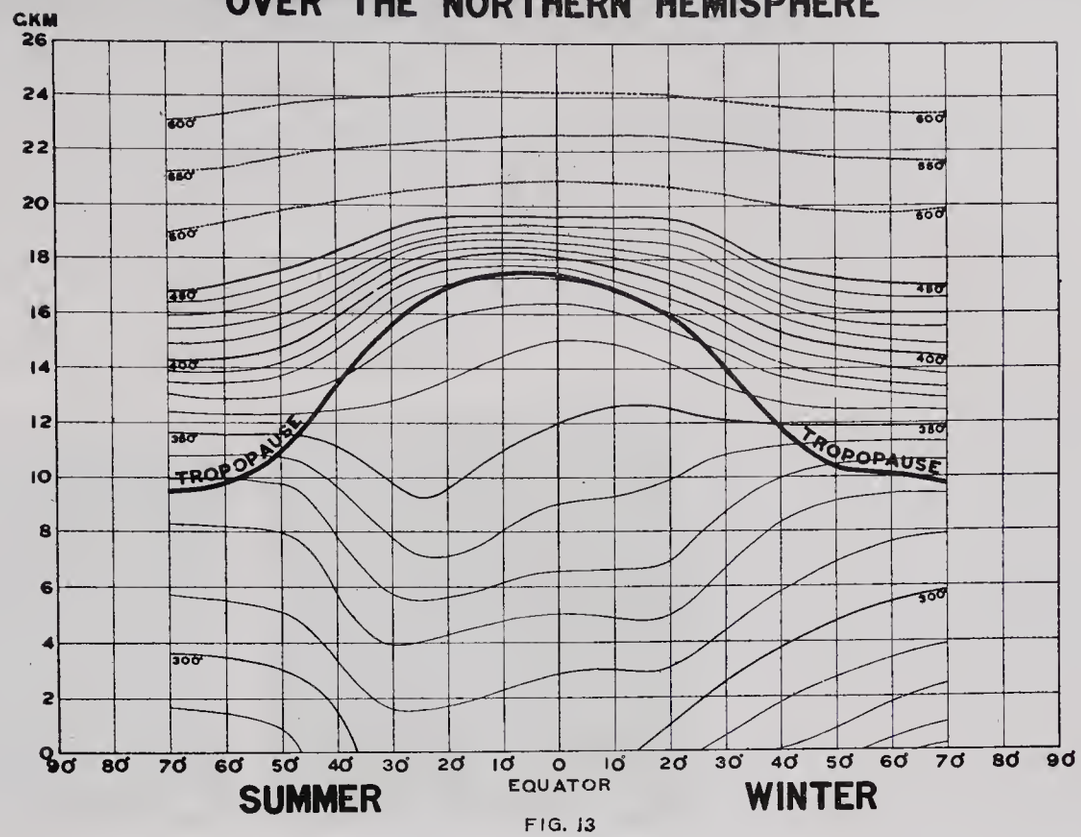
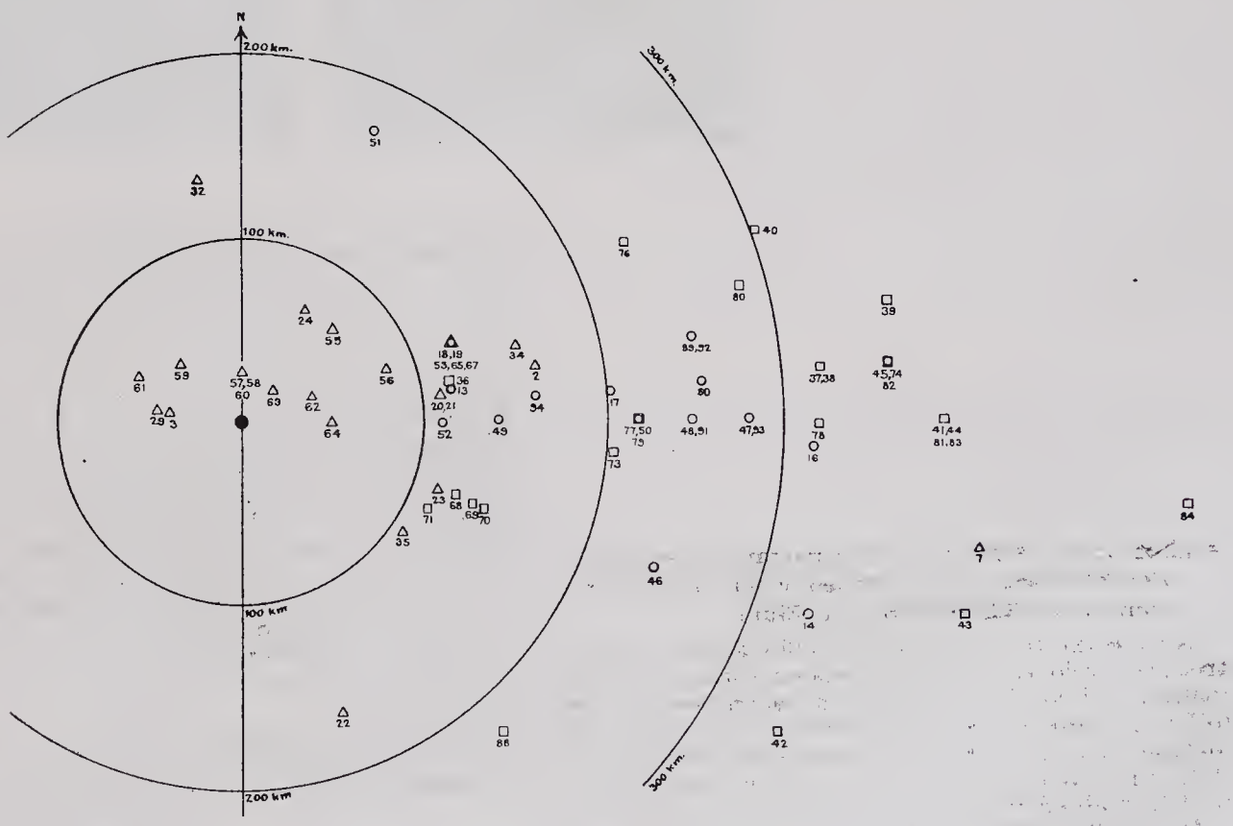


FIG. 13

PLACES OF FALL OF METEOROGRAPHS SENT UP WITH SOUNDING BALLOONS FROM AGRA JULY 1925 — MARCH 1928



○ MARCH TO MAY △ JUNE TO 15TH OCTOBER □ 16TH OCTOBER TO FEBRUARY

FIG. 14

G.P.Z.O Poona, 1930.

by strewing aluminium powder on its surface. With water, however, the movement is so rapid that it is often difficult to follow its details. Melted spermaceti, in which aluminium powder is suspended, is a very convenient medium for the demonstration and study of fronts and vortices similar to those which occur on a much larger scale in Nature.

If a shallow layer of spermaceti is heated in a flat enamel dish over a plate of copper or brass, then, as is well known, the liquid layer is divided up into a series of small polygonal cells with liquid rising at the centres of the cells and falling at their peripheries. If, now, a cylindrical rod is moved across the liquid with its axis vertical, the formation of the Kármán double row of vortices can be distinctly seen. By

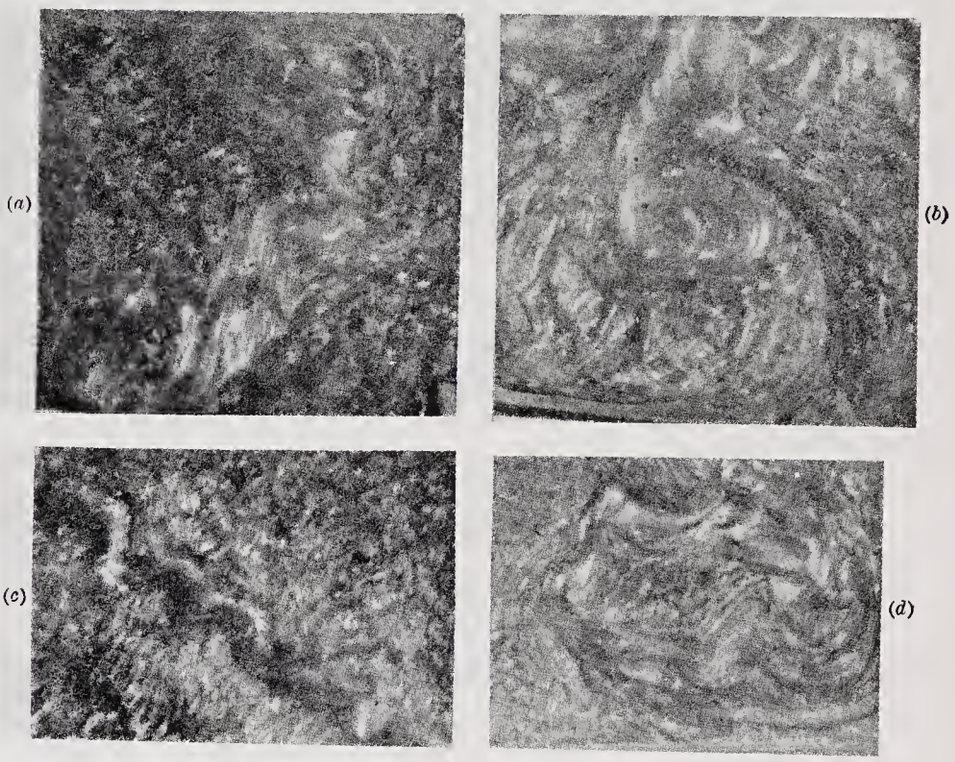


FIG. 1.

substituting a thin small-angled wedge of wood with its narrow end dipping in the liquid, and moving it across the surface with its axis inclined, a wave motion is set up, and the stream which flows past the thicker end of the wedge rolls up into a succession of vortices which persist for some time before they disappear. The development of these vortices resembles in many ways the development of a cyclone by the incursion of a tongue of warm air in cold air. Fig. 1 (*a*) and (*b*) shows photographs of such waves and vortices, the area of disturbance being obviously larger in the latter case. When the liquid is at a low temperature, or when the speed of movement of the wedge is small, waves are set up without the formation of vortices, similar to those studied in the atmosphere by Bergeron and Swoboda (Fig. 1 (*c*)). By giving a circular movement to the wedge, the series of cyclones along the polar front can be neatly imitated (Fig. 1 (*d*)).

The interesting question as to how far the instability of the liquid layer helps the formation and persistence of these vortices is being examined.

K. R. RAMANATHAN.
SOBHAG MAL.

Meteorological Office, Poona,
Dec. 23.

[1] K. R. Ramanathan and A. A. Narayan Iyer: "The Structure and Movement of a Storm in the Bay of Bengal during January 1929".

A Laboratory Method of demonstrating the Formation of Fronts and Vortices when there is discontinuous Movement in a Fluid.

ACCORDING to views now generally accepted, extra-tropical cyclones are formed along surfaces of kinematical discontinuity between air-masses having different temperatures and moisture-contents, and during their growth they possess an asymmetrical structure. Recent studies [1] of tropical cyclones show that they also have often a similar origin and structure.

It is well known that vortices can easily be formed in a fluid by producing a sufficiently sharp discontinuity of velocity—as by suddenly moving a half-immersed spoon across the surface of water. A common method of studying stream-lines in water is

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Nature, 127, 272, 1931.

THE STRUCTURE OF THE SEA-BREEZE AT POONA.

By K. R. Ramanathan, M.A., D.Sc.

(*Received on 14th March 1931.*)

Summary.—The paper forms a preliminary study of the structure of the sea-breeze which sets in from a westerly to a northwesterly direction at Poona on many evenings in the months February to May. Observations with special pilot balloons made on four days in February to April 1930, considered along with the autographic records at the surface, show that the sea-breeze has the characteristics of a cold front. It is found that an easterly return current in the upper layers begins about an hour before the advent of the sea-breeze. The thickness of the breeze is usually 1—1·5 km. but occasionally it extends to as much as 2·0 km. It is suggested that the breeze from the Arabian Sea gets revived on passing over the Western Ghats owing to the flow down the slope on the eastern side of the Ghats and the higher temperature of the surface air which it meets on the Deccan plateau.

Observations made within the last two years at Poona show that during the months February, March, April and part of May there occurs on many days a sudden onset of fresh gusty wind generally between 15 and 17 hrs. This wind usually comes from some west-north-westerly direction and is slightly cooler and moister than the air previously present. It was considered probable that this regular evening breeze was actual sea-breeze that was penetrating inland. In order to test whether this is so, Dr. Desai and the present writer went on 3rd March 1930 to Lonavla, which is about 33 miles to the WNW of Poona. On that day, a west-north-westerly breeze set in at Lonavla at 16 h. 5 m., with the same suddenness as was usual at Poona and the strength of the wind at an exposed site was 12—15 miles per hour. The wind continued at about the same strength till at least 18h. 30m. The usual west-north-westerly evening breeze at Poona began on that day at 19 h. 25 m. There was thus a time-interval of 3 h. 20 m. between the onset of the breeze at Lonavla and Poona. The calculated speed of the sea-breeze front is about 10 m. p. h. which is slightly less than the average speeds of wind at Lonavla and Poona. We may therefore take it that a front was advancing towards ESE on the afternoon of that day.

In order to study the structure of the breeze a number of pilot balloons were let off before and after the commencement of the breeze on a few days in the hot season of 1930. *Fig. 1* shows the changes of wind, temperature and humidity on the afternoon of 27th February 1930. It will be seen that the breeze commenced at about 18 h. 20 m. on that day. Pilot balloons were sent up at 17 h. 0 m., 17 h. 22 m., 18 h. 20 m. and 18 h. 36 m. The balloons were provided with tails of 50 metres length and flags were attached at $6\frac{1}{4}$ metres, $12\frac{1}{2}$ metres and 50 metres from the balloon. A sand bag weighing 31 gms. was also attached at the end of the string, partly to keep the tail more nearly vertical and partly to reduce the rate of ascent. The trajectories and tables giving the velocities at different heights of the four balloons are shown in *Fig. 2*. The following points are noteworthy :—

(1) The wind-structure at 17 h. 22 m. was practically identical with that at 17 h. 0 m. above 2·2 km., but the later ascent shows a south-easterly to east-south-easterly wind between 0·5 km. and 2·2 km.

Ind. Met. Dept. Sci. Notes, 3, No. 30, 131–134, 1931.

(2) At 18 h. 20 m., that is, two minutes after the commencement of the breeze at the surface, the westerly wind had penetrated to a height of 0·6 km. and after a region of weak winds up to above 1·2 km. there was a gradually increasing easterly wind up to 3·1 km. (It must be remembered that 0·6 km. represents the thickness of the westerly wind not at the place where the balloon was released but at a distance of about 2 km. to the east of the observatory.)

(3) At 18 h. 36 m., the direction of wind had changed from westerly to north-westerly and its thickness had increased to 1·2 km.; this was succeeded by an east-south-easterly wind which extended to above 2·3 km.

The approximate structure of the advancing sea-breeze as constructed out of the pilot balloon winds is as given in *Fig. 3(a)*. In drawing the diagram the fact that the position of the balloon alters with time has been taken into account. It is evident that the sea air was advancing inland as a cold front with a thickness of about 1·2 km., with a return current of land air above. The trajectories at 17 h. 22 m. and 17 h. 0 m. show that the easterly return current was noticeable about an hour before the arrival of the cold air at the surface, but was not noticeable about an hour and a half earlier.

The difference in the character of the gustiness before and after 18 h. 18 m. is noteworthy,—the former being of the convective eddy type produced by ground heating and the latter of the type produced by movement of stable air over rough ground. Considering that the latter type of wind persisted till about 20 h. 50 m. and that the average speed of wind between 18 h. 20 m. and 20 h. 50 m. was about 8 m.p.h., the farthest distance inward that the sea air would have travelled is about 20 miles to the east of Poona. This is, however, an overestimate and it is probable that the actual distance was smaller, as, with the progress of the night, the contrast between the original and incoming air would become smaller.

Although the balloons were of the same size and had the same net free lift, the rates of ascent were different, and showed variations with height. Owing to the large influence of eddies, however, it is impossible to say definitely whether there was any difference in the rates of ascent in the two air masses. The height curves, however, suggest that in the neighbourhood of the nose of the front, both within and above the cold air mass, there was a slight upward component of velocity, and that about 6 km. behind there was a downward component of motion in the air above 1·2 km.

A second series of four ascents were made on 12th March 1930, but unfortunatley on this day, although the breeze started at 16 h. 25 m., the first ascent was only made at 17 h. 22 m. The other three ascents were made at 17 h. 37 m., 18 h. 8 m. and 18 h. 31 m. The wind before the onset of the breeze was indefinite in direction and of the average velocity of about 5 m. p. h. The fresh breeze came from the north-west with an average velocity of about 16 m. p. h. and a maximum gust velocity of about 30 m. p. h. The anemogram, thermogram and hygrogram are reproduced in *Fig. 4* and the horizontal projection of the trajectories of the four balloons are shown in *Fig. 5*. It will be noticed that the colder current extended to a height of 1·5—2·0 km. and the return upper current to 3·5—4·0 km. and that between 17 h. 22 m. and 18 h. 30 m., there was not much variation in the depth of the current. In the first two flights, however, the maximum wind velocity at about 0·2 km. and the rate of decrease of velocity above that level were greater than in the last two. The height-time curves also show that the rates of ascent of the balloons were generally smaller in the lower current than in the upper. There was a depression over the Punjab on the morning of this day, which weakened and moved over to the United Provinces by the 13th morning.

On 21st March 1930, a series of five flights were made between 15 h. 34 m. and 17 h. 53 m. The breeze set in at 16 h. 35 m. and was accompanied by a slight fall of temperature. There was a feeble gradient for soutnerly to south-westerly wind.

The wind direction was variable—between E. and S.—for an hour before the ascent and changed to west-north-westerly with the setting in of the breeze (see *Fig. 6*). The mean speed of wind rose from about 5 m. p. h. to about 12 m. p. h. An interesting feature of this day's wind was that it persisted till after 22 h. 30 m., or for a period of about 6 hrs.

The horizontal projection of the trajectories of the balloons are drawn in *Fig.* 7. A diagram showing the structure of the breeze similar to the one for 27th February 1930 is given in *Fig* 3 (*b*). It will be noticed that as on 27th February 1930, the counter current set in even before the advent of the surface wind. The westerly current had grown to a thickness of 1 km. in less than half an hour. Its thickness was 1·3 km. after 45 minutes and 1·1 km. after 1 h. 20 m. It appears therefore that in this case also the rate of rise of thickness was very high in the first few minutes and that the thickness remained more or less steady afterwards. It may be mentioned that the second and third balloons were lost in cumulus cloud. In order to study how the current dies off at night, it would be necessary to make use of balloons provided with lights and it is hoped to do this in the coming season.

Owing to the long duration of the breeze on this day, it is likely to have penetrated inland to a distance of 40—50 miles east of Poona. The question as to how the strength and thickness of the breeze dies down with distance inland remains to be worked out.

As an instance of a slightly more complicated situation, one may take the breeze on 4th April 1930. On the morning of this day, there was a shallow low over the west Central Provinces and W. Central India which had moved slightly eastwards by next morning. The autographic records are given in *Fig. 8* and the balloon trajectories at 16 h. 49 m., 17 h. 45 m. and 18 h. 46 m. are shown in *Fig. 9*. The thermograph trace and the nature of the gustiness in the anemogram show that the sea-breeze came on at about 18 h. 40 m. But the wind was fresh and from a north-westerly direction even from 15 h. 30 m. It will be seen from the velocity tables that the maximum speed of wind increased in the successive flights and it is probable that the thickness of the north-westerly or west-north-westerly current underwent a sudden increase at 18 h. 40 m.

With the progress of the hot season, the surface wind at Poona in the afternoon hours becomes more and more westerly long before the onset of the sea-breeze, but even then, on most days, one can detect the arrival of the sea-breeze by the change in the type of gustiness.

It is clear from the above that the sea-breeze at Poona comes on as a cold front. When the air is dry, there is little effect on the weather, but when some moisture has already been injected into the atmosphere at 1—3 km. by previous weather conditions (as often happens in April and May), the coming in of the breeze acts as a trigger for the production of cumulus cloud and sometimes even for the development of a thunderstorm.

There remains the important question as to whether the breeze at Poona is to be looked upon as mere ordinary sea-breeze or there are other causes helping to strengthen it and make it more marked. The usual thickness of the sea-breeze near coast stations in India is only about 0·5 to 0·7 km. but here we have seen instances when the westerly current went up to more than 2 km. above Poona. The Western Ghats are about 30 miles to the west of Poona and the coast is about 40 miles farther

to the west. Poona is on the Deccan tableland at a height of about 1,800 ft. above sea-level while the Ghats rise to a height of about 2,500 ft. and the coastal plain west of the Ghats is generally lower than 300 ft. with a few low hills rising here and there. When the see-breeze is to the west of the Ghats, it may be only of the usual thickness and the return current may take place towards the sea above 0·7 or 0·8 km., but when the breeze reaches the Ghats, part of it is lifted up and overflows, the flow being greatest wherever there are cols in the Ghats. Once over the Ghats, the sea air would meet air heated by contact with the surface of the plateau and will therefore have a tendency to spread inland displacing warmer air. We have yet no definite information regarding the depth of the sea-breeze at a place west of the Ghats. It is planned to make a more detailed study of the effect in the summer of 1931 especially in the neighbourhood of the Ghats.

The special pilot balloon observations utilised in this note were carried out enthusiastically by the staff of the Upper Air Section at Poona. Mr. K. P. Ramakrishnan, Assistant in the section, also gave considerable help during the preparation of the note.

M15DGofOb—15-8-31—350—GIPS

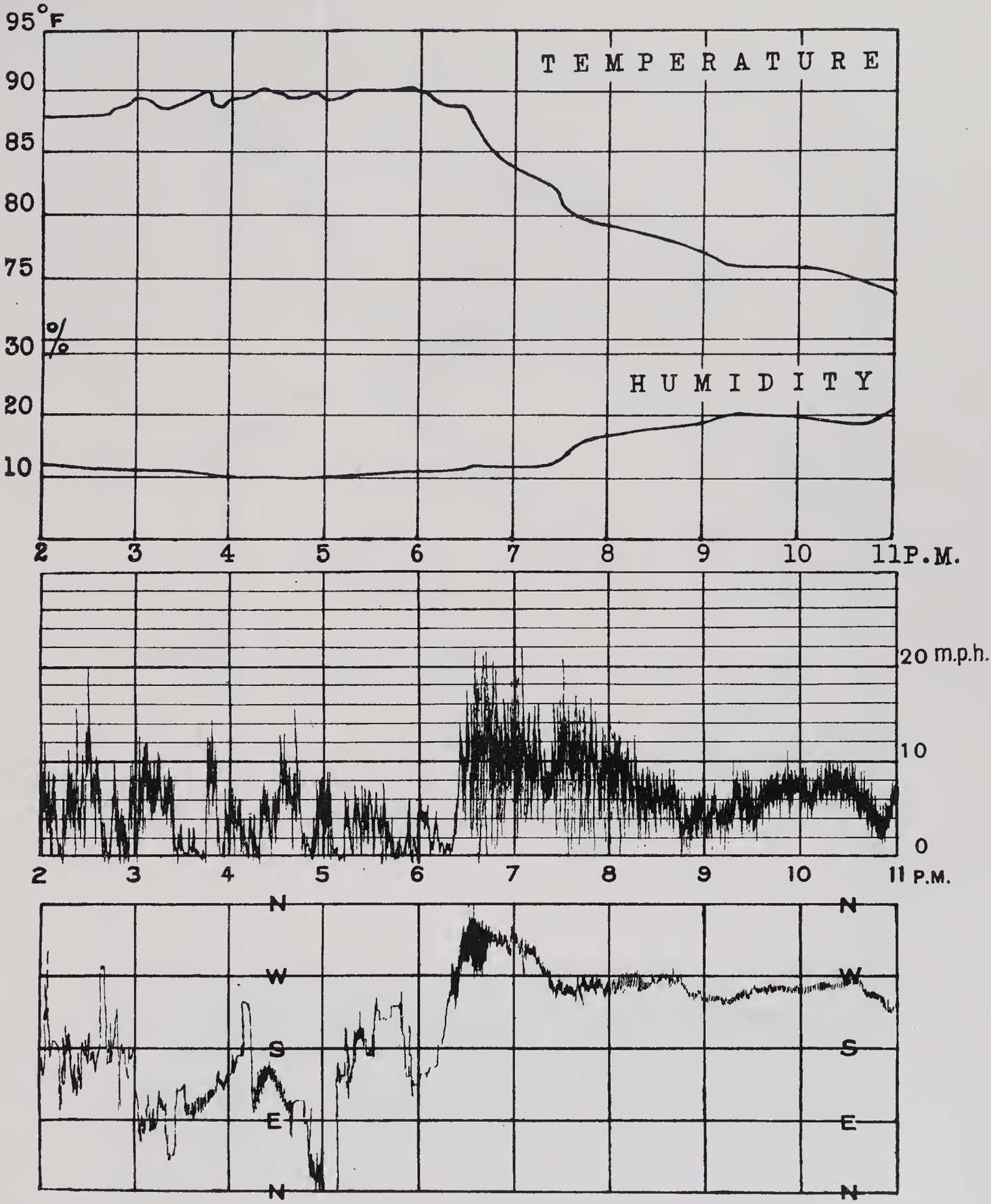
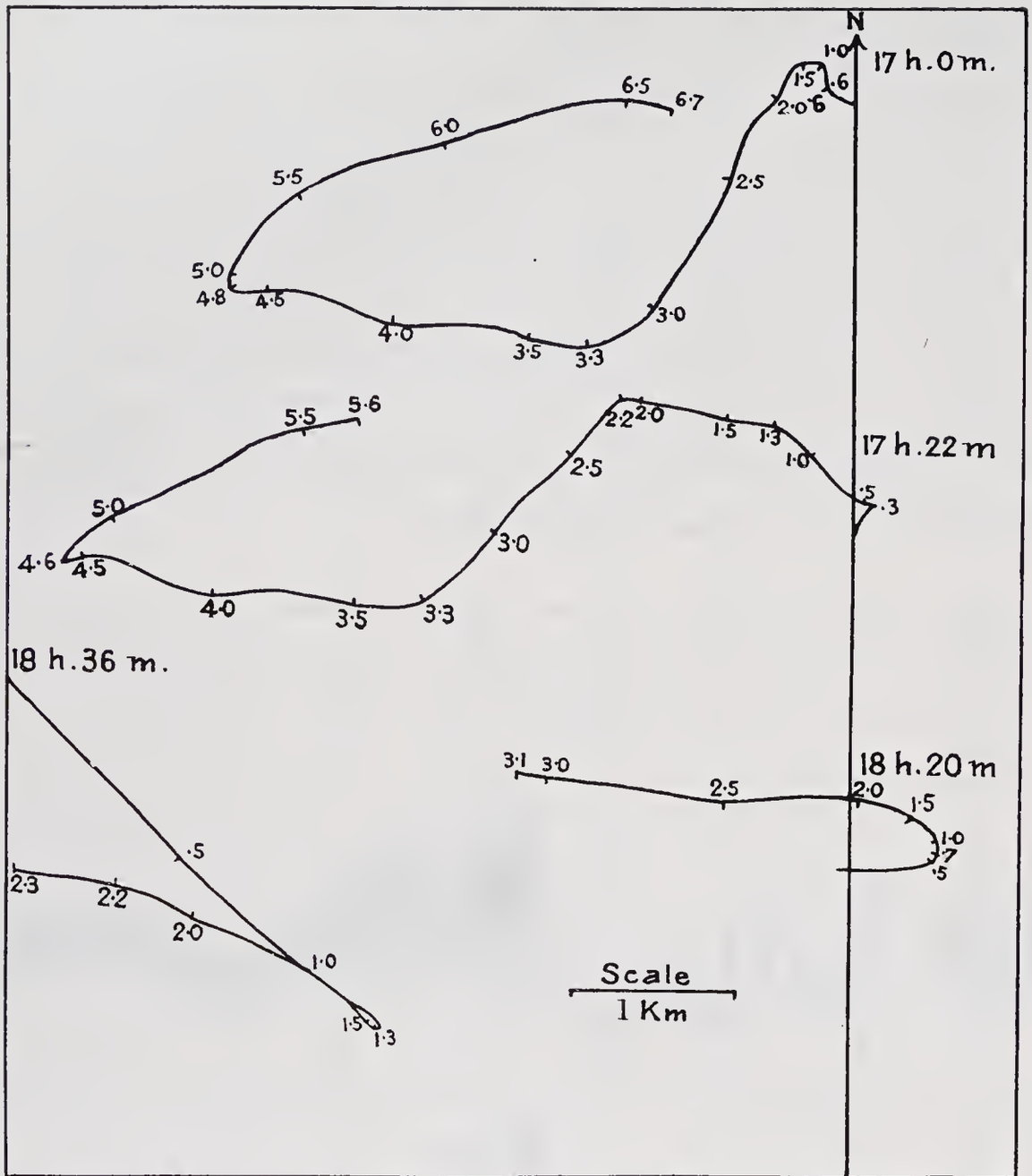


Fig. 1. Temperature, humidity and wind at Poona on 27-2-1930.



17h 0m		17h 0 m		17h 22m		17h 22m		18h 20m		18h 36m	
Km.	m/s	Km.	m/s	Km.	m/s	Km.	m/s	Km.	m/s	Km.	m/s
Gr.	1.2	4.0	3.4	Gr.	1.0	3.0	4.6	Gr.	0.3	Gr.	2.7
0.5	1.6	4.5	2.2	0.3	1.2	3.3	4.9	0.2	4.3	0.5	6.9
1.0	1.0	4.8	1.0	0.5	0.8	3.5	4.3	0.5	1.8	1.0	5.4
1.5	1.0	5.0	2.4	1.0	2.7	4.0	3.9	0.7	1.1	1.3	0.5
2.0	2.1	5.5	4.8	1.5	3.6	4.5	1.9	1.0	1.2	1.5	3.3
2.5	4.6	6.0	5.8	2.0	1.8	4.6	1.3	1.5	2.6	2.0	4.4
								2.0	3.1		
3.0	5.0	6.5	5.8	2.2	2.5	5.0	3.9	2.5	6.1	2.3	7.6
3.5	4.2			2.5	4.6	5.5	5.3	3.0	6.9		

Fig.2. Trajectories of Pilot Balloons sent up on the afternoon of 27. 2. 1930 from Poona and wind velocity tables obtained from them.

G. P. O. 1931.

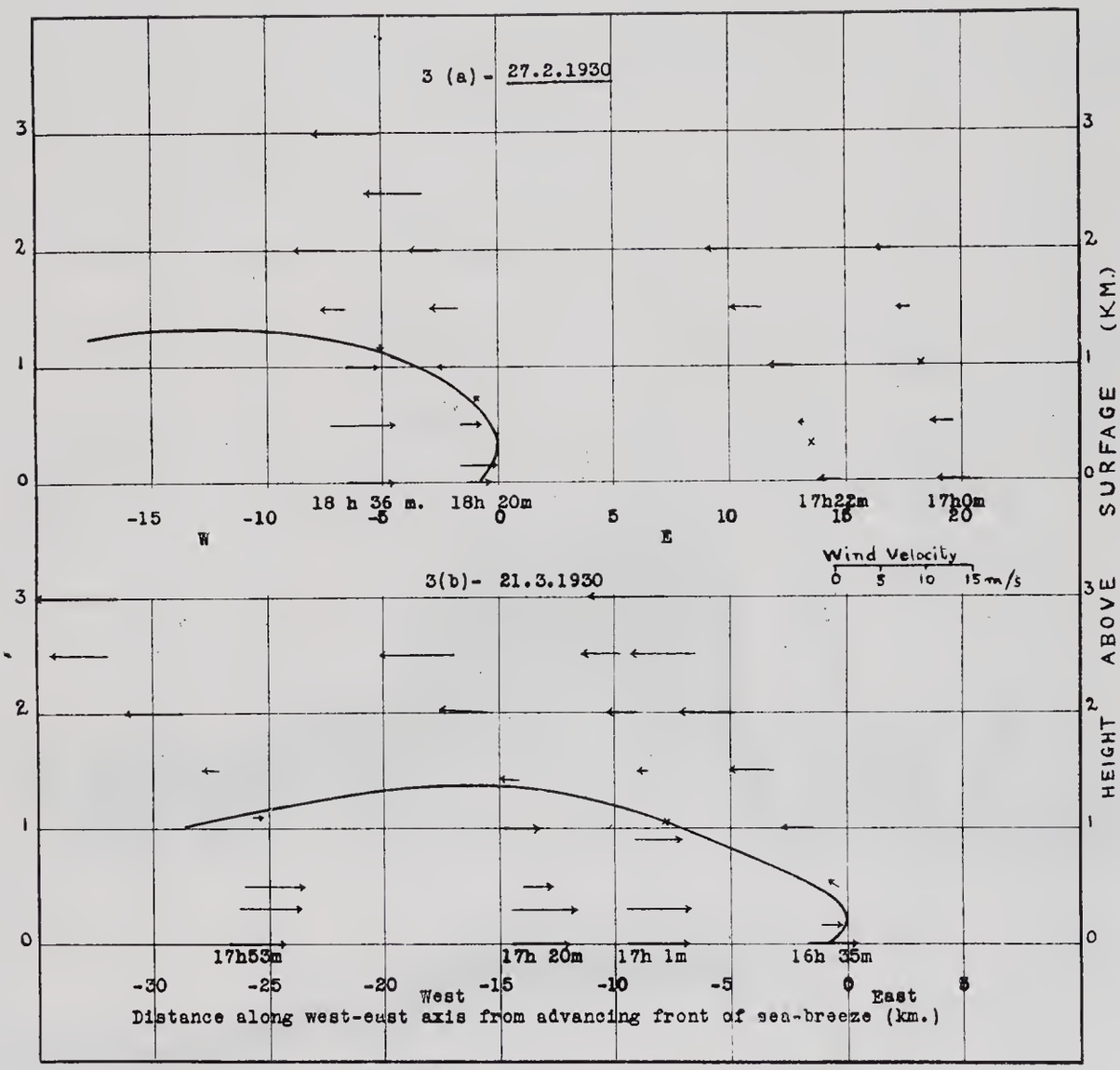


Fig.3. Structure of the sea-breeze on 27.2.1930 and 21.3.1930 as constructed out of the pilot balloon ascents.

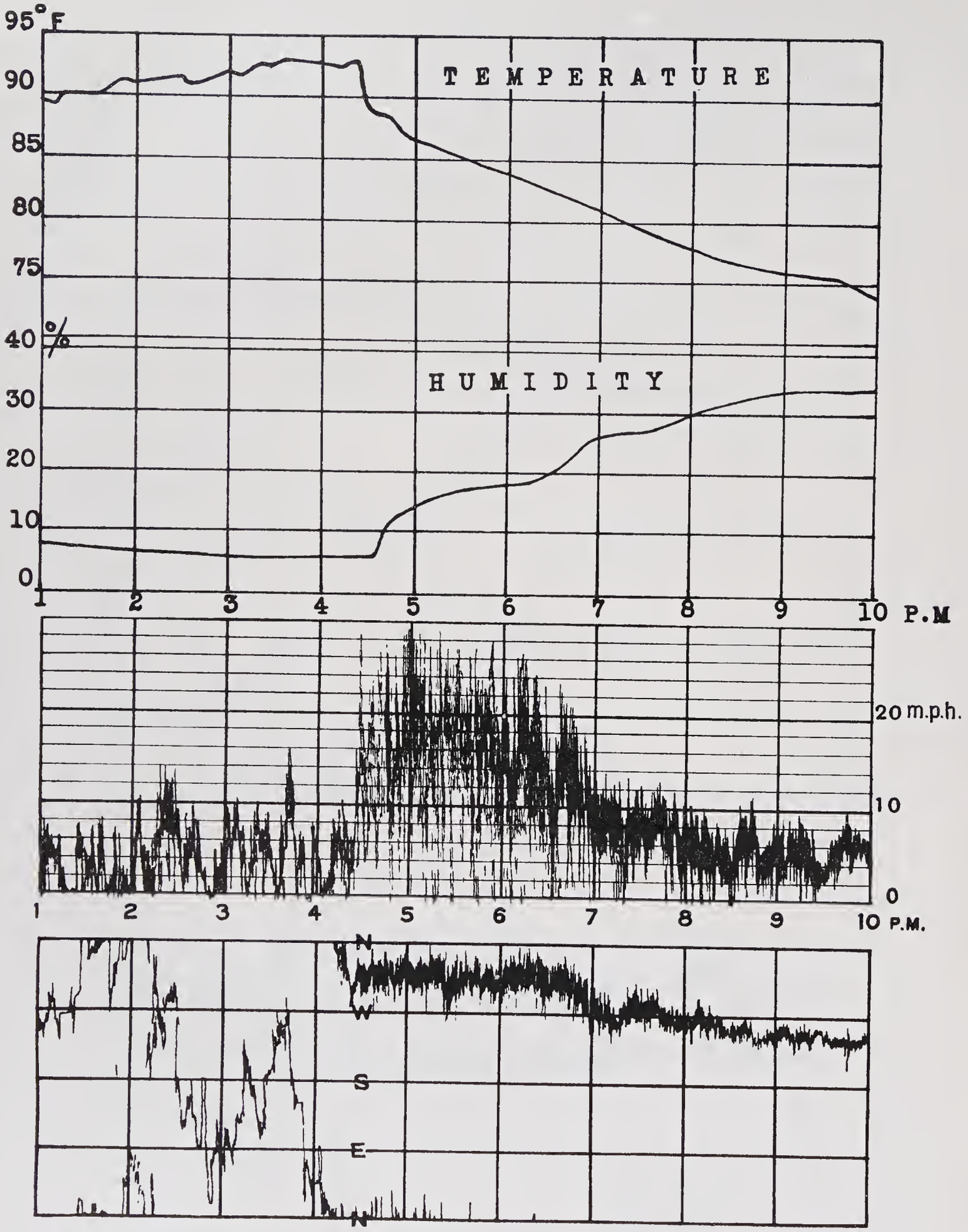
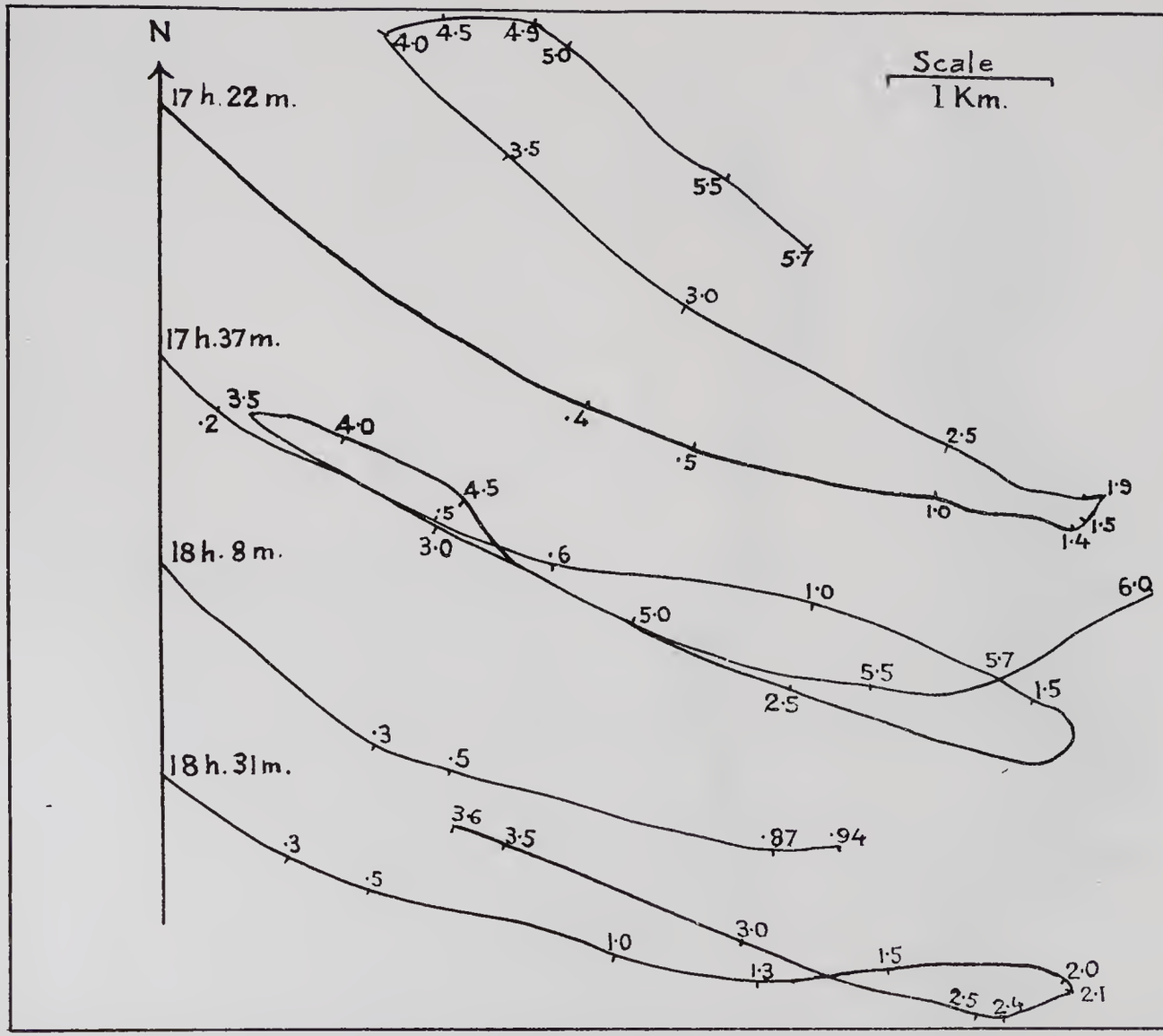


Fig. 4. Temperature, humidity and wind at Poona on 12-3-1930.



17h 22 m		17h 37 m		18 h 8 m	
Km.	m/s	Km.	m/s	Km.	m/s
Gr.	7.2	Gr.	7.6	Gr.	6.8
0.5	18.0	0.2	7.8	0.2	9.5
0.5	10.0	0.5	14.6	0.5	7.9
1.0	4.7	0.6	8.0	0.9	6.0
1.5	1.6	1.0	6.5	18 h 31 m.	
2.0	0.9	1.5	2.7	Km.	m/s
2.5	5.6	1.9	1.4	Gr.	4.5
3.0	7.7	2.0	3.0	0.5	8.4
3.5	8.3	2.5	7.2	1.0	8.0
4.0	0.8	3.0	8.1	1.5	6.0
4.5	4.6	3.4	0.3	2.0	2.0
5.0	3.9	4.0	2.6	2.5	4.8
5.5	8.0	4.5	3.0	3.0	7.2
		5.0	6.3	3.5	8.7
		5.5	6.3		
		6.0	7.4		

Fig.5. Trajectories of Pilot Balloons sent up on the afternoon of 12. 3. 1930 from Poona and wind velocity tables obtained from them.

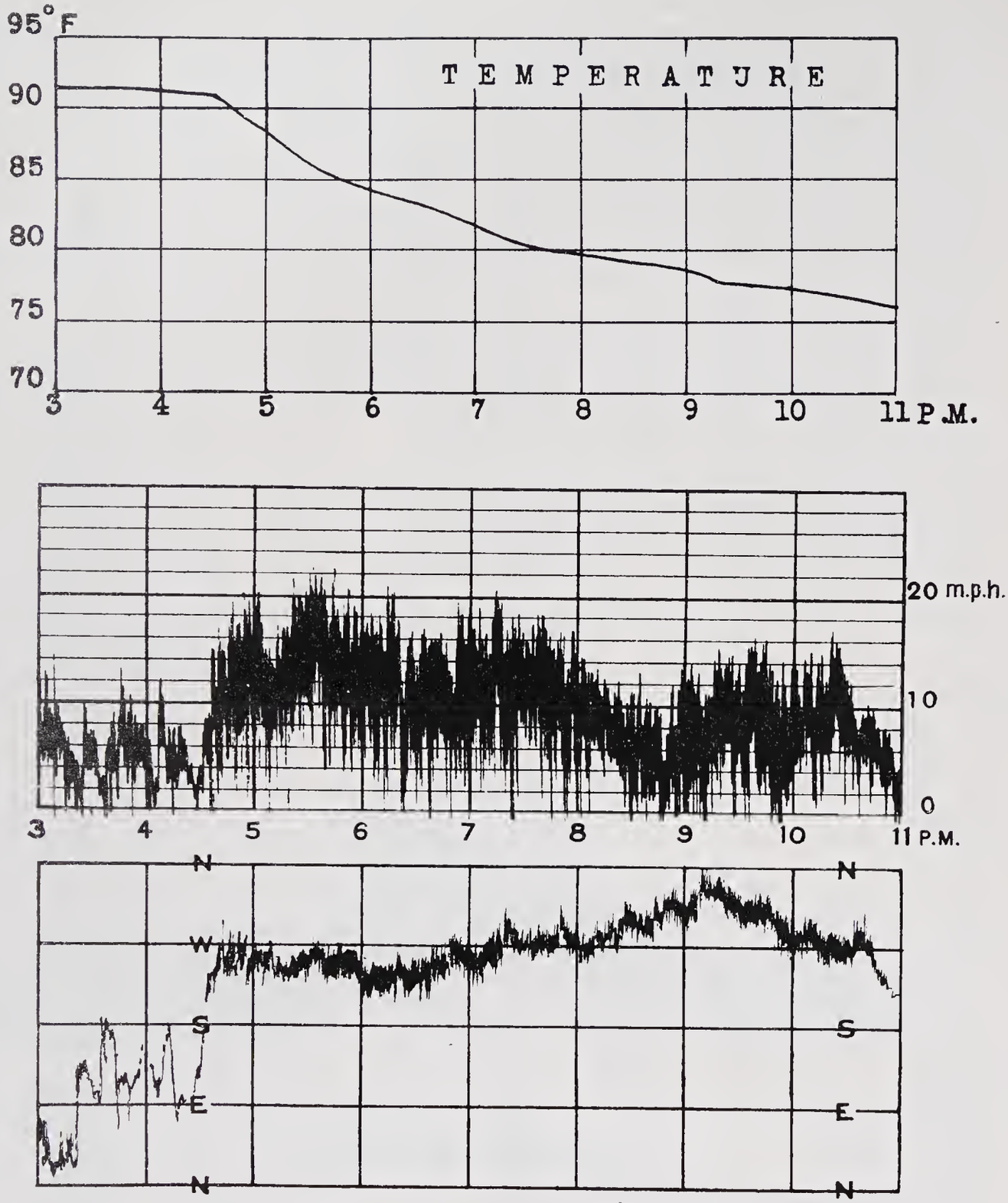
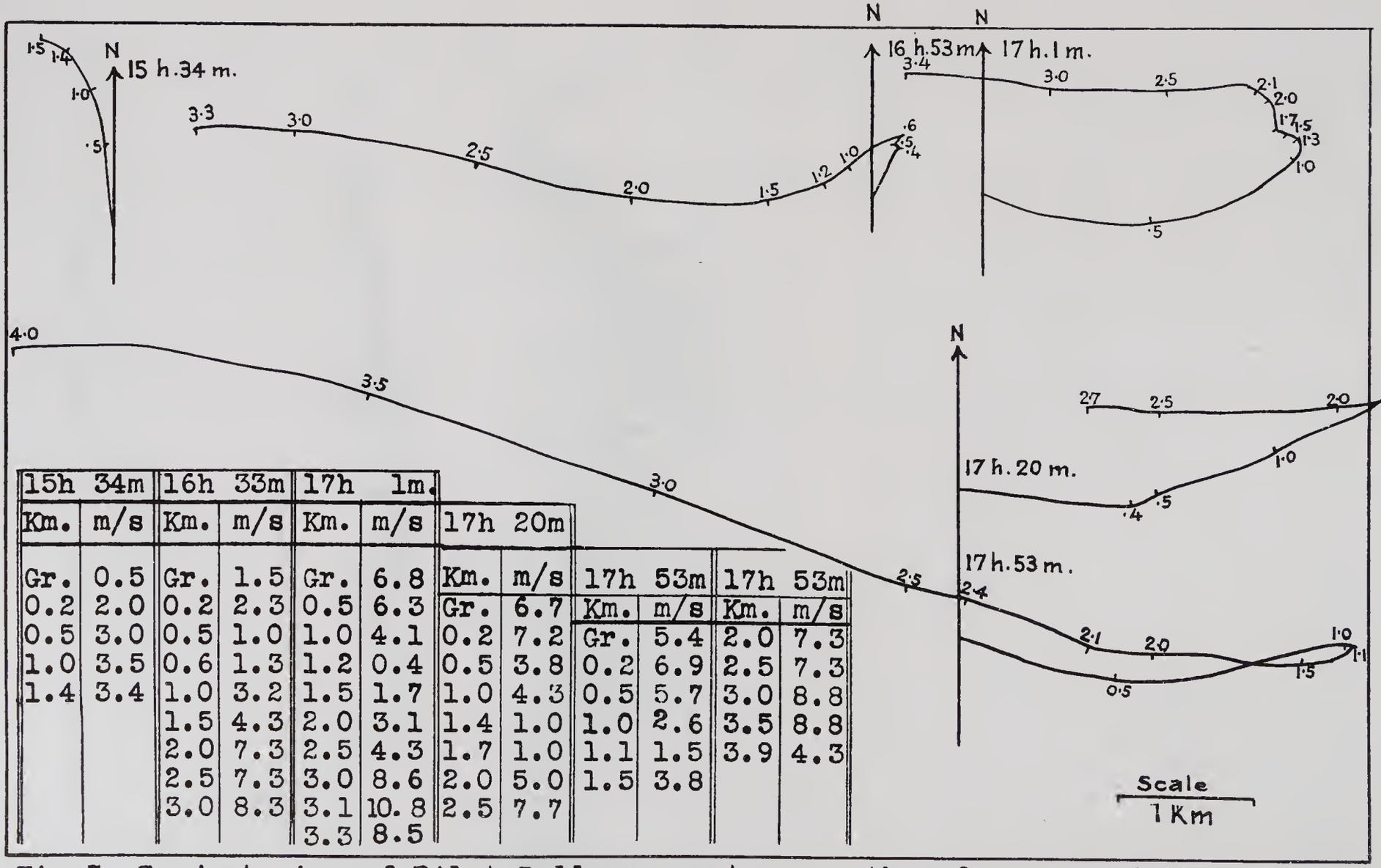


Fig. 6. Temperature and wind at Poona on 21-3-1930.



15h 34m		16h 33m		17h 1m.		17h 20m					
Km.	m/s	Km.	m/s	Km.	m/s	Km.	m/s	17h 53m		17h 53m	
								Km.	m/s	Km.	m/s
Gr.	0.5	Gr.	1.5	Gr.	6.8	Gr.	6.7	Gr.	5.4	2.0	7.3
0.2	2.0	0.2	2.3	0.5	6.3	0.2	7.2	0.2	6.9	2.5	7.3
0.5	3.0	0.5	1.0	1.0	4.1	0.5	3.8	0.5	5.7	3.0	8.8
1.0	3.5	0.6	1.3	1.2	0.4	1.0	4.3	1.0	2.6	3.5	8.8
1.4	3.4	1.0	3.2	1.5	1.7	1.4	1.0	1.1	1.5	3.9	4.3
		1.5	4.3	2.0	3.1	1.7	1.0	1.5	3.8		
		2.0	7.3	2.5	4.3	2.0	5.0				
		2.5	7.3	3.0	8.6	2.5	7.7				
		3.0	8.3	3.1	10.8						
				3.3	8.5						

Fig.7. Trajectories of Pilot Balloons sent up on the afternoon of 21. 3. 1930 from Poona and wind velocity tables obtained from them.

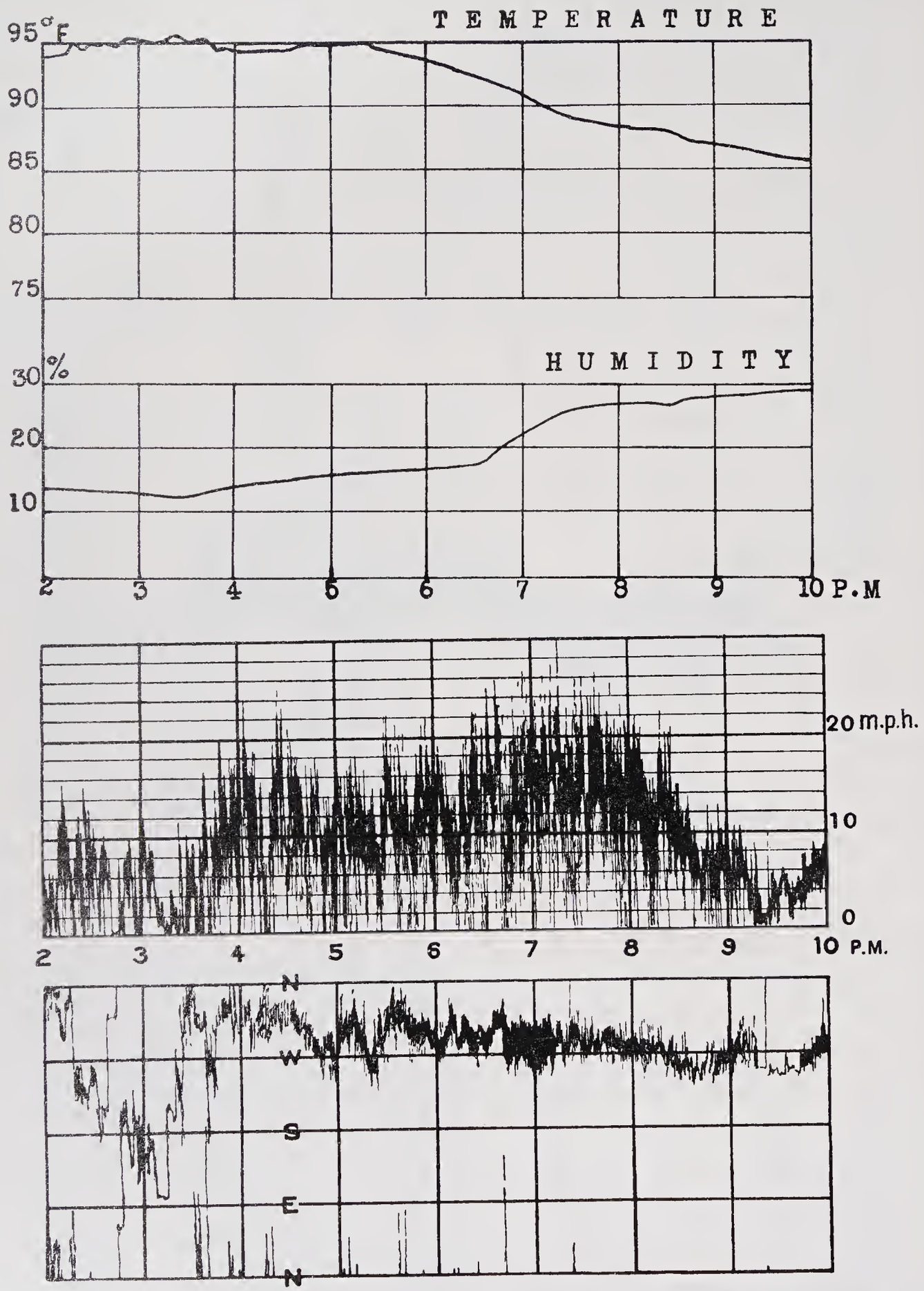
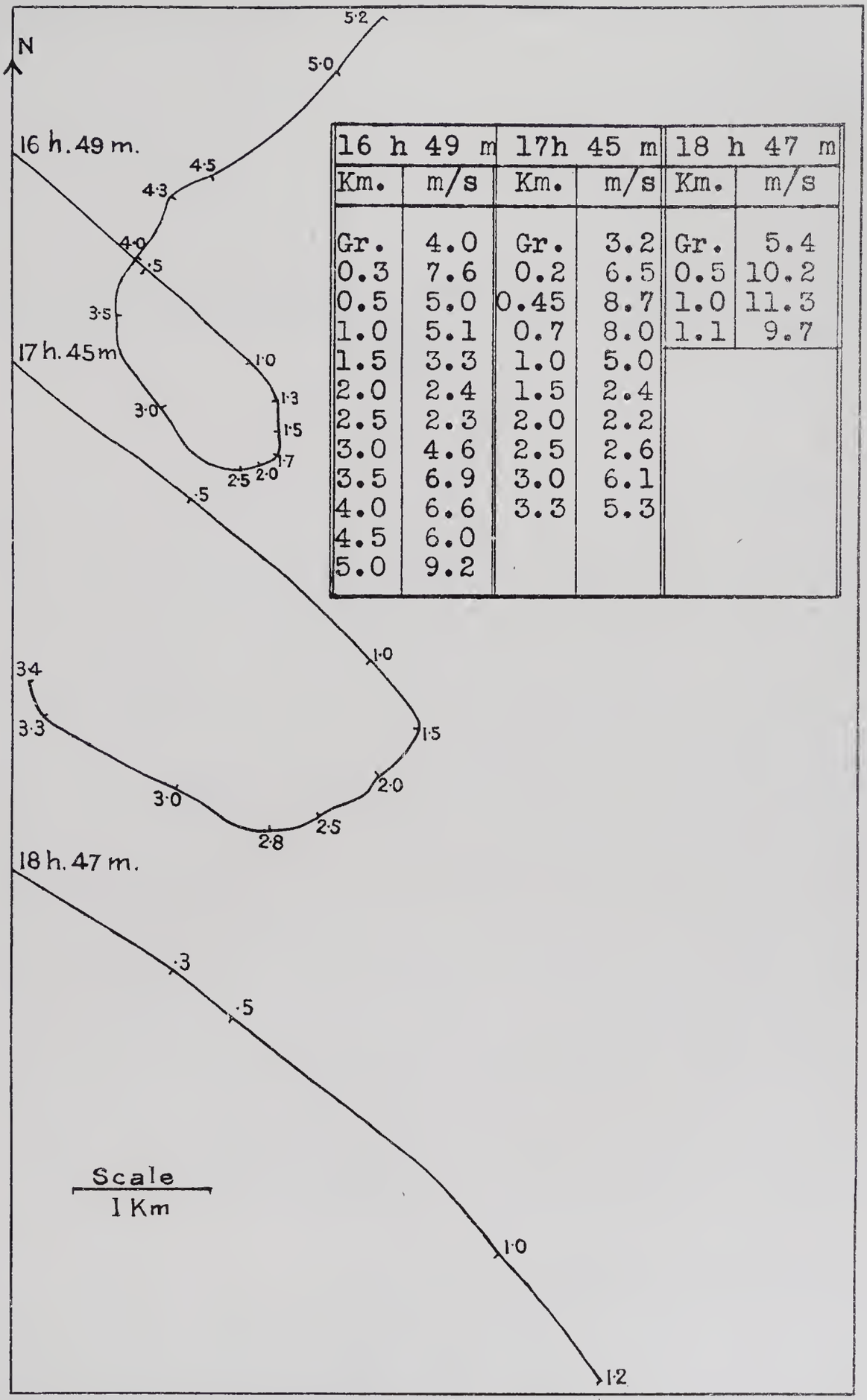


Fig. 8. Temperature, humidity and wind at Poona on 4-4-1930.



16 h 49 m		17h 45 m		18 h 47 m	
Km.	m/s	Km.	m/s	Km.	m/s
Gr.	4.0	Gr.	3.2	Gr.	5.4
0.3	7.6	0.2	6.5	0.5	10.2
0.5	5.0	0.45	8.7	1.0	11.3
1.0	5.1	0.7	8.0	1.1	9.7
1.5	3.3	1.0	5.0		
2.0	2.4	1.5	2.4		
2.5	2.3	2.0	2.2		
3.0	4.6	2.5	2.6		
3.5	6.9	3.0	6.1		
4.0	6.6	3.3	5.3		
4.5	6.0				
5.0	9.2				

Fig.9. Trajectories of Pilot Balloons sent up on the afternoon of 4. 4. 1930 from Poona and wind velocity tables obtained from them.

Effect of radiation on the equilibrium of the higher layers of the troposphere and the nature of the transition from troposphere to stratosphere.

By *K. R. Ramanathan*, Poona.

With 8 figures.

Introduction.

The low temperatures and sharp inversions characteristic of the tropical tropopause have not yet received a satisfactory explanation. An associated striking characteristic of the distribution of temperature in the tropical atmosphere is the frequent occurrence of high lapse-rates, often approaching and sometimes exceeding that of dry air adiabatic, between about 8 and 14 km. This feature is very pronounced in the results of sounding balloon ascents over north India [1] during the months June to October and over Java [2] and the peninsular portion [3] of India in all parts of the year. These high lapse-rates occur both in clear and cloudy weather. In temperate latitudes also, a layer of maximum lapse-rate is generally met with in the upper part of the troposphere, at heights of 6 to 8 km [4], the height decreasing with decrease in height of the tropopause [5]. In a recent interesting paper, *F. Albrecht* [6] has pointed out that the loss of heat by radiation in the sub-stratosphere would result in the setting up of high lapse-rates there.

In this paper, the loss or gain of heat by each kilometre layer of the upper half of the troposphere due to absorption and emission of both long-wave and solar radiation has been evaluated assuming different values of moisture-content in these atmospheric layers. The moisture is assumed to be entirely in the form of vapour. The calculations show that as a necessary consequence of the very low temperatures at the base of the stratosphere over the tropics, there should be a region of active convection between about 8 and 12 km and weaker convection for two or three kilometres further above, both during day and night. It is suggested that by a cycle of cause and effect the radiation helps to maintain the high levels and low temperatures of the tropical tropopause.

Data used and the method of calculation.

From *Hettner*'s [7] and *Paschen*'s [8] experimental results on the absorption of water-vapour, curves showing the variation of transmission with wave-length were prepared for the following eleven ranges of wave-lengths: 1.08—1.2 μ, 1.25—1.50 μ, 1.7—2.0 μ, 2.3—3.0 μ, 5—6 μ, 6—7 μ, 7—8 μ, 13—16 μ, 16—20 μ, 20—30 μ and 30—34 μ corresponding to known quantities of water-vapour in the

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path of the radiation. Other ranges of wave-length for which either the energy of radiation or the absorption in the higher layers of the troposphere was comparatively small, were neglected. From these curves, derived curves of transmission for five other quantities of water-vapour were prepared — assuming *Beer*'s law to hold[1]. The integrated percentage transmissions for each of these ranges of wave-lengths were then plotted against the logarithms of precipitable water (see Fig. 2) as has been done by *Abbot* [9] in his paper on "the Radiation of the planet Earth to space". From these curves, the transmissions for any quantity of moisture in the path of the radiation could be read off.

For the regions 2.3—3.0 μ and 13—16 μ where absorption by carbon dioxide is strong, similar transmission curves were prepared for varying quantities of carbon dioxide using the experimental results of *C. Schaefer* and *B. Philipps* [10] for the former region and those of *Rubens* and *Aschkinass* [11] for the latter. For computing the absorption produced by any layer, the transmissions through the water-vapour and carbon dioxide contained in the layer were compounded by multiplication. The transmission curves for wave-lengths shorter than 3 μ are used for the calculation of the absorption of solar radiation in the atmosphere and those for 5 μ and above for calculating the emission and absorption of atmospheric radiation. The *net long-wave* atmospheric radiation becomes negligibly small for wave-length shorter than 6 μ.

The emission of radiation from any layer within each of the above-mentioned ranges of wave-lengths was obtained by multiplying the black-body radiation at the mean temperature of the layer by the fraction representing the absorption in that layer. A convenient table of black body radiation in different ranges of wave-lengths is given by *Abbot* in his paper referred to above. Equal amounts of energy are supposed to be radiated from the upper and lower boundaries of the layer. Owing to the diffuseness of the radiation, the length of path in any layer is on the average greater than the thickness of the layer and in order to allow for this, the amount of absorbing material in the layer was supposed to be twice the actual amount. This does not, however, apply to the absorption of solar radiation, where the actual amount of absorbing material along the ray in the layer, depending on the altitude of the sun, was taken. The energy of solar radiation just outside the earth's atmosphere was calculated with the help of data given in the International Critical Tables on the assumption that the sun radiates as a black body at 6000° A.

1) The assumption of *Beer*'s law regarding the absorption of water-vapour and carbon dioxide in the atmosphere is open to criticism. *Hettner*'s experiments were made with water-vapour at atmospheric pressure and temperatures 81° C or 127° C. *Rubens* and *Aschkinass*' observations were also at atmospheric pressure and temperature. It is known from the experiments of *Eva Bahr*, *Hertz*, *Schaefer* and others that the character and intensity of the absorption bands of a gas depend to some extent on its pressure and temperature and if mixed with other gases, on the nature and presence of the added gases (cf. *Schaefer* and *F. Matossi*: *Das Infrared Spectrum*, J. Springer, Berlin). Insufficient resolution of the absorption lines in the experiments would also invalidate the application of *Beer*'s Law. But with the quantitative data available at present, it seems impossible to introduce greater precision. Accurate data regarding absorption of both water-vapour and carbon dioxide under conditions such as occur in the neighbourhood of the tropopause are very much needed.

The numbering of the layers was done according to their temperatures in the manner adopted by *Simpson* in his famous papers on Atmospheric Radiation [12] — the layer + 1 having a mean temperature of 223° A, + 2 having 229° A and so on, the mean temperature increasing by 6° A for each increase of number of layer by 1. Proceeding in the opposite direction, the layer — 1 has a mean temperature of 217° A, — 2 a temperature of 211° and so on. The calculations were carried out for two values of humidity 100% and 25%. It must not, however, be overlooked that considerable supersaturation is possible in the higher layers of the troposphere. From an admirable series of experiments, *C. F. Powell* [13] obtained the following values of supersaturation at the cloud limit in rapidly-expanded dust-free air.

Initial Temp. ° C	Expansion rates v_2/v_1	Final Temp. ° C	Super-Saturation
77	1.252	47	2.87
50	1.286	19.1	3.74
35	1.314	3.2	5.07
18	1.370	— 16.4	7.80
7	1.375	— 26.4	8.95

The super-saturation increases with decreasing temperatures; it would therefore not be surprising if the upper layers of the tropsphere are highly supersaturated at times when there is an accumulation of moist air in the lower levels.

Moisture in the Stratosphere.

A question of some difficulty is that of the moisture-content of the stratosphere. Assuming that the temperature at the base of the tropopause is 220° A, that the air there is saturated and that the distribution of moisture in the stratosphere is given by *Dalton*'s law, *Simpson* adopted 0.03 cm of precipitable water as the probable moisture-content of the stratosphere. *Abbot* states that there are many occasions when the *total* amount of water-vapour over Mount Montezuma in Chile, altitude 2710 m, as determined from the spectro-bolograms obtained there approached the value adopted by *Simpson* and that it is therefore likely that the moisture-content of the stratosphere is considerably smaller than the value assumed by *Simpson*. Over the tropics at any rate, the moisture-content in the stratosphere must be much less than 0.03 cm as the temperature of the tropical tropopause is almost invariably lower than 200° A. The saturation vapour pressure of water at 220° A is 0.027 mb, while at 200° A, it is only 0.0016 mb [14]. This difference while not in any way affecting *Simpson*'s results regarding the atmosphere as a whole, will be of great influence in determining the radiation equilibrium of the higher layers of the troposphere. In the present paper, the values of radiation of different atmospheric layers have been calculated assuming the effective temperature of the stratosphere to be 220° A for the following values of precipitable water in the atmosphere above layer — 3; .03 cm, .01 cm and .0015 cm. The last of these values corresponds approximately to the water-content in the stratosphere on the assumption that the temperature at its base is 200° A and that the distribution of moisture therein is governed by *Dalton*'s law.

Results.

The method of calculation will be clear from the following example. In Fig. 1 are drawn the absorption curves of water-vapour in the wave-length range 16—20 μ for the following seven values of moisture-content: — .1 cm, .05 cm,

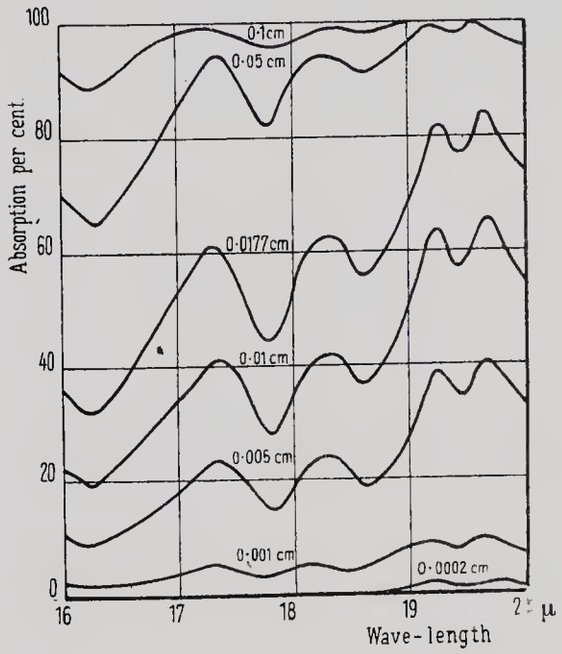

Fig. 1.

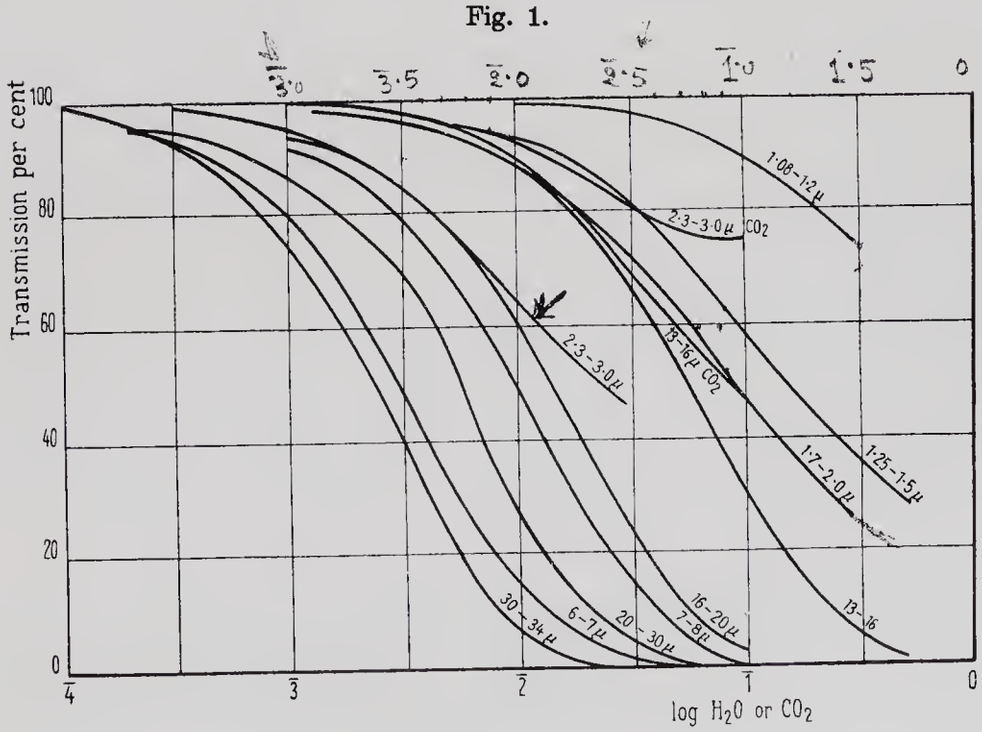

Fig. 2.

.0177 cm, .01 cm, .005 cm, .001 cm and .0002 cm. Of these, the third is *Hettner*'s experimental curve and the others are derived from this using *Beer*'s law. The corresponding percentages of absorption are 98, 88, 59, 41, 23, 5 and 1. These are plotted against the logarithms of moisture-content in Fig. 2 (curves for other regions of the long-wave spectrum are also drawn in the same figure). Using this

curve, tables similar to Table 1 for calculating the net radiation loss from each layer under different assumptions regarding moisture-content of the atmosphere were prepared.

Table 1.

Atmospheric Radiation 16—20 μ; unit = cal. cm^{-2} min^{-1} $\times$ 10^{-4}.

(Assumed relative humidity in troposphere = 100%; moisture-content of stratosphere = .0015 cm of precipitable water.)

Atmospheric layer	Assumed mean temperature of layer	Percentage absorption in layer	Downward and upward radiation from each layer	Total downward radiation ↓	Total upward radiation ↑	Total radiation entering layer ↓+↑	Absorption in layer	Emission from layer	Net radiation from layer
1	2	3	4	5	6	7	8	9	10
	220	16							
			54 10 31 56 80 98 65 21 2	54	363				
−3	205	4				422	17	20	3
			52 10 32 58 84 102 68 22 2	62	368				
−2	211	11				440	48	64	16
			46 9 32 65 95 115 76 25 2	87	378				
−1	217	20				478	96	130	34
			37 7 26 65 118 144 95 31 3	135	391				
1	223	33				543	179	236	57
			25 5 17 43 118 215 142 46 5	208	408				
2	229	55				637	350	430	80
			12 2 8 20 53 215 315 102 12	310	429				
3	235	75				768	576	630	54
			3 1 2 5 13 54 315 409 49	393	458				
4	241	90				879	790	818	28
			0 0 0 1 1 5 31 409 486	447	486				
5	247	100				972	972	972	0
			0 0 0 0 0 0 0 0 486	525					

The numbers in column 4 below the diagonal line represent the downward and those above the line the upward radiation. For example, 118 $\times$ 10—^{4} cal/cm^2 is radiated by layer 1 every minute both upwards and downwards. Of the downward radiation, 53 units pass through layer 2, 13 units through layers 2 and 3, 1 unit through layers 2, 3 and 4, and so on. The values in column 5 give the total atmospheric radiation passing through the boundaries between different layers and represent the sum of the figures in column 4 to the left of the diagonal line. Similarly, the figure in column 6 represents the total upward atmospheric radiation. The sum of the downward radiation passing through the upper boundary of the layer and the upward radiation passing through the lower boundary are given

in column 7. This, multiplied by the fraction representing absorption in the layer gives the energy absorbed in it. The other columns are self-explanatory.

In Tables 2 (a) und (b) are collected together the values of gain of energy by long wave radiation of the layers + 6 to — 3 assuming the moisture-content of the stratosphere to be .0015 cm and the relative humidity in the tropospheric layers to be 100 and 25 per cent, corresponding to cases (a) and (b) respectively. In the same tables, the rate of absorption of energy per sq. cm from solar radiation (1) when the rays are incident normally and (2) when the secant of the sun's zenith distance is 2, are also given. All the absorption bands due to water-vapour in the region 0.9—3.0 μ and the carbon dioxide band near 2.7 μ have been taken into account. The carbon dioxide is supposed to be present in a constant proportion of 0.03 per cent in all layers.

Table 2.

Net radiation from different layers of the atmosphere. Unit = cal cm^{-2} $min^{-1} \times 10^{-4}$.

Precipitable water in stratosphere assumed to be 0.0015 cm.

(a) Relative humidity in troposphere assumed to be 100 per cent.

Atmospheric layer (1)	Rate of absorption of solar radiation: Normal incidence (2)					Sec Z = 2 (3)					Rate of absorption due to long-wave radiation (4)							Total rate of gain of energy due to radiation 5 = (3) + (4)
	1.08—1.2 μ	1.25—1.5 μ	1.7—2.0 μ	2.3—3.0 μ	Total	1.08—1.2 μ	1.25—1.5 μ	1.7—2.0 μ	2.3—3.0 μ	Total	6—7 μ	7—8 μ	13—16 μ	16—20 μ	20—30 μ	30—34 μ	Total	
str.	0	13		84		0	13											
— 3	0	0	0	28	28	0	0	0	21	21	3	1	9	— 3	— 23	— 3	— 16	5
— 2	0	13	6	38	57	0	13	6	26	45	3	0	3	— 16	— 51	— 9	— 70	— 25
— 1	0	26	12	49	87	0	19	12	30	61	2	1	— 6	— 35	— 72	— 12	— 122	— 61
1	0	38	24	57	119	0	30	25	31	86	0	— 3	— 14	— 57	— 75	— 7	— 156	— 70
2	10	66	51	65	192	10	63	41	26	140	— 1	— 6	— 20	— 81	— 48	— 2	— 158	— 18
3	20	116	83	55	274	15	93	60	15	183	0	— 8	— 32	— 54	18	0	— 112	71
4	30	167	109	33	339	25	114	60	7	206	0	0	— 35	— 27	0		— 62	144
5	50	230	125	17	422	40	127	51	3	221		1	— 26	0			— 25	196
6	70	250	102	6	428	65	102	29	—	196			— 9				— 9	187

(b) Relative humidity in troposphere assumed to be 25 per cent.

str.	0	13		84		0	13											
— 3	0	0	0	25	25	0	0	0	17	17	1	0	10	0	— 3	0	8	25
— 2	0	0	0	29	29	0	0	0	18	18	2	0	5	1	— 9	— 4	— 5	13
— 1	0	0	6	33	39	0	6	3	19	28	2	0	— 1	— 7	— 27	— 7	— 40	— 12
1	0	13	6	35	54	0	13	6	21	40	0	0	— 5	— 22	— 55	— 11	— 93	— 53
2	0	26	12	42	80	0	19	12	22	53	— 4	— 3	— 12	— 45	— 78	— 13	— 155	— 102
3	0	38	24	49	111	0	30	23	23	76	— 1	— 10	— 20	— 66	— 84	— 16	— 197	— 121
4	10	61	45	51	167	10	52	36	18	116	— 3	— 11	— 22	— 71	— 49	— 10	— 166	— 50
5	20	104	73	42	239	15	85	53	11	164	3	— 11	— 25	— 70	— 16	— 2	— 121	43
6	30	148	162	28	368	20	108	59	5	192	.	— 8	— 25	— 43	— 8	.	— 84	108
											.	.	— 26	— 9	.		— 35	

A summary of data for the cases when the precipitable water above — 3 is 0.01 cm and 0.03 cm is given in Tables 3 and 4.

Table 3.

Net radiation from different layers of the atmosphere. Unit = cal cm^{-2} $min^{-1} \times 10^{-4}$. Precipitable water in stratosphere assumed to be 0.01 cm. stratosphere above − 3.

(a) Relative humidity in troposphere assumed to be 100 per cent.

Atmospheric layer (1)	Rate of absorption of solar radiation: Normal incidence (2) 1.08—1.2 μ	1.25—1.5 μ	1.7—2.0 μ	2.3—3.0 μ	Total	Sec Z = 2 (3) 1.08—1.2 μ	1.25—1.5 μ	1.7—2.0 μ	2.3—3.0 μ	Total	Rate of absorption due to long-wave radiation (4) 6—7 μ	7—8 μ	13—16 μ	16—20 μ	20—30 μ	30—34 μ	Total	Total rate of gain of energy due to radiation 5 = (3) + (4)
str.	15	92	70	187	364	15	85	65	120	285								
− 3	0	0	0	17	17	0	0	.	11	11	4	3	17	3	+ 4	5	36	47
− 2	0	12	5	21	38	0	11	5	15	31	6	3	9	0	+ 7	6	31	62
− 1	0	24	11	36	71	0	17	10	17	44	5	6	0	− 6	10	2	17	61
1	0	35	21	52	108	0	27	21	20	68	0	3	− 8	−18	− 8	1	− 30	38
2	10	57	46	43	156	10	51	33	17	111	− 2	− 1	−23	−32	−16	− 3	− 77	34
3	20	110	75	38	243	15	83	50	10	158		− 6	−29	−32	− 9		− 76	82
4	30	158	98	25	311	25	100	48	5	178		0	−32	−21			− 53	125
5	50	215	110	29	404	40	113	41	2	196			−25	− 1			− 26	170
6	70	235	92	5	402	65	91	23	.	179			− 9				− 9	170

(b) Relative humidity in troposphere assumed to be 25 per cent.

str.	15	92	70	187	364	15	85	65	120	285								
− 3	0	0	0	15	15	0	0	0	10	10	1	1	15	0	5	2	24	34
− 2	0	0	0	19	19	0	0	0	11	11	2	2	9	4	10	3	30	41
− 1	0	6	5	21	32	0	5	3	12	20	6	1	4	0	5	2	18	38
1	0	12	5	23	40	0	11	5	13	29	7	3	− 1	− 5	− 4	0	0	29
2	0	24	9	26	59	0	17	9	14	40	2	0	− 8	−19	− 7	− 2	− 34	6
3	0	35	21	35	91	0	27	20	14	61	2	− 4	−17	−31	−26	− 2	− 78	− 17
4	10	57	41	37	145	10	41	29	11	91		− 6	−18	−37	−23	− 7	− 91	0
5	20	98	66	33	217	15	75	42	7	139		− 9	−27	−44	−10		− 90	49
6	30	139	145	32	346	20	94	47	3	164		− 7	−23	−23	− 8		− 61	103

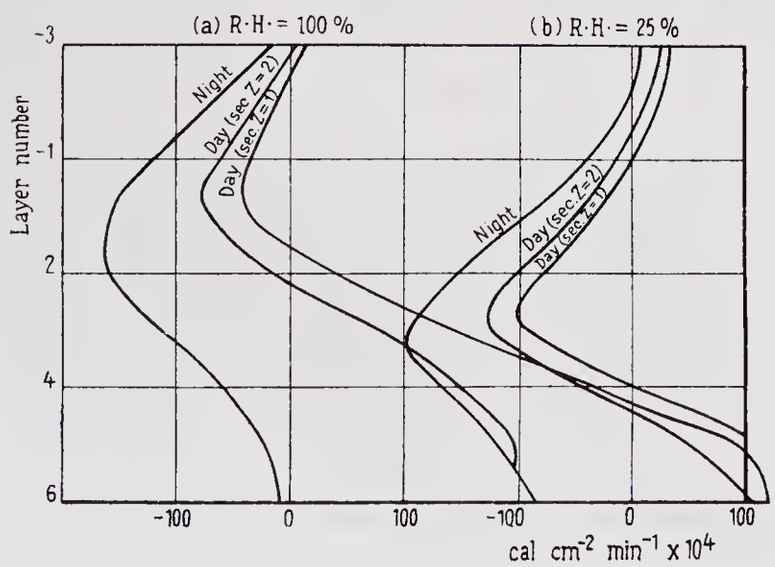

Fig. 3. Net rate of gain of energy by radiation by different atmospheric layers. Moisture in stratosphere assumed to be .0015 cm.

Table 4.

Net radiation from different layers of the atmosphere. Unit = cal cm^{-2} $min^{-1} \times 10^{-4}$.
Precipitable water in stratosphere assumed to be 0.03 cm.

(a) Relative humidity in troposphere assumed to be 100 per cent.

Atmospheric layer	Rate of absorption of solar radiation										Rate of absorption due to long-wave radiation							Total rate of gain of energy due to radiation 5 = (3) + (4)
	Normal incidence					Sec Z = 2												
	(2)					(3)					(4)							
(1)	1.08—1.2 μ	1.25—1.5 μ	1.7—2.0 μ	2.3—3.0 μ	Total	1.08—1.2 μ	1.25—1.5 μ	1.7—2.0 μ	2.3—3.0 μ	Total	6—7 μ	7—8 μ	13—16 μ	16—20 μ	20—30 μ	30—34 μ	Total	
str.	30	236	174	258	698	30	197	127	153									
—3	0	0	0	13	13	0	.	2	8	10	5	3	22	7	9	5	51	61
—2	0	11	4	15	30	0	10	6	11	27	6	4	16	12	19	8	65	92
—1	0	22	9	26	57	0	13	7	11	31	5	8	7	12	26	2	60	91
1	0	31	17	28	76	0	22	15	13	50	0	6	1	3	6	1	17	67
2	10	51	37	34	132	10	47	25	11	93	—2	1	—11	—14	—10	— 3	— 39	54
3	20	96	60	20	196	15	66	37	7	125		—6	—22	—16	—13		— 57	68
4	30	138	80	18	266	23	81	37	3	144		1	—28	—16	1		— 42	102
5	50	184	91	10	335	40	90	31	1	162			—22	2			— 20	142
6	70	205	74	4	353	65	68	17	0	150			— 9				— 9	141

(b) Relative humidity in troposphere assumed to be 25 per cent.

str.	30	236	174	258	698	30	197	127	153	507								
—3	0	0	0	10	10	0	0	0	7	7	2	1	11	1	7	2	24	31
—2	0	0	0	14	14	0	0	0	7	7	3	3	18	3	14	3	44	51
—1	0	0	4	15	19	0	5	0	9	14	5	2	12	5	11	4	39	53
1	0	11	4	17	32	0	9	3	9	21	3	4	9	5	6	3	30	51
2	0	22	9	18	49	0	13	7	9	29	—2	3	— 1	— 2	7	0	5	34
3	0	31	17	23	71	0	22	13	9	44	—1	—3	—10	— 9	—14	— 2	— 39	5
4	10	50	33	24	117	10	39	21	7	77	—3	—5	—16	—16	—18	— 7	— 65	12
5	20	86	53	21	180	15	60	32	5	112		—8	—18	—17	— 9		— 52	60
6	30	121	117	14	282	20	75	36	3	134		—7	—20	—16	— 8		— 51	83
													—25	— 7			— 32	

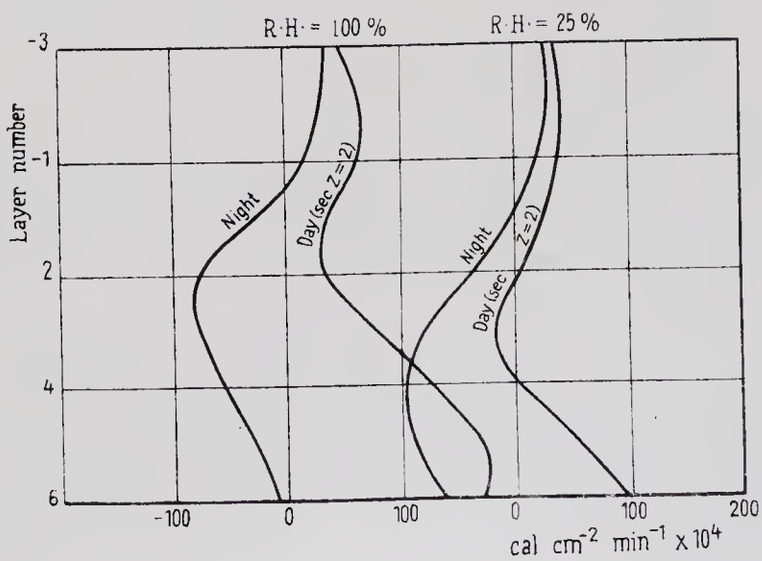

Fig. 4. Net rate of gain of energy by radiation by different atmospheric layers. Moisture in stratosphere assumed to be .01 cm.

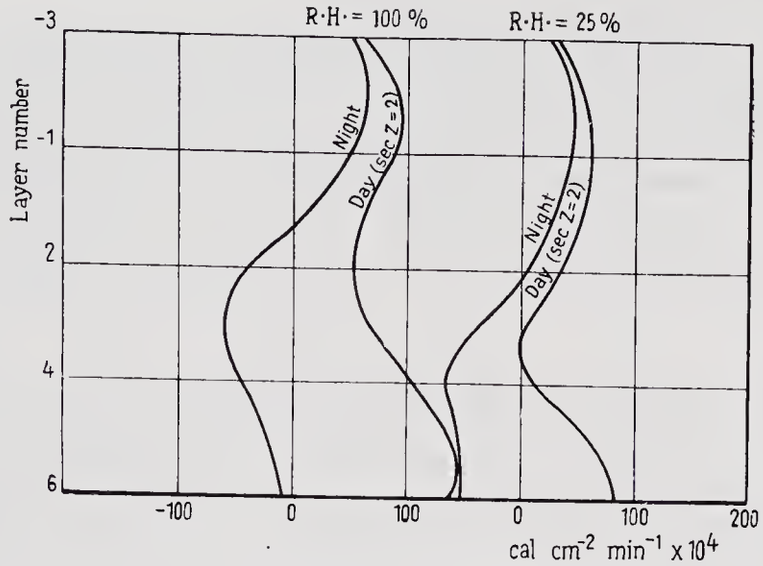

Fig. 5. Net rate of gain of energy by radiation by different atmospheric layers. Moisture in stratosphere assumed to be .03 cm.

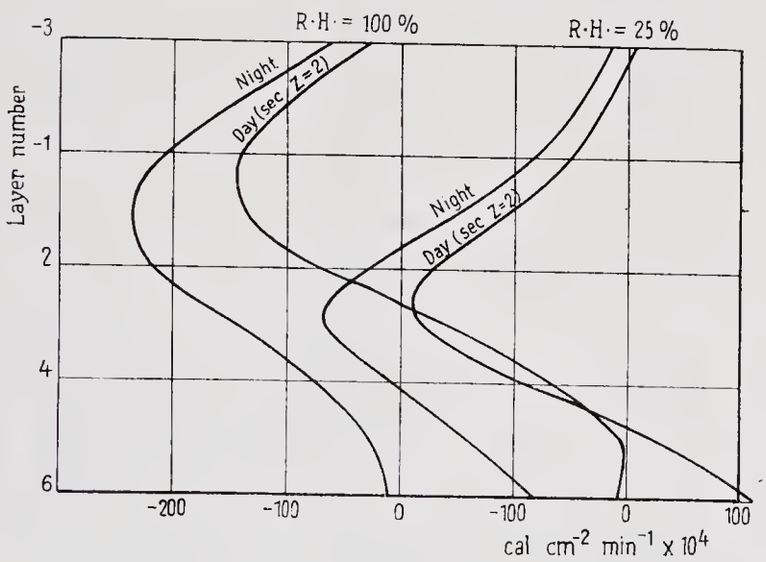

Fig. 6. Net rate of gain of energy by radiation by different atmospheric layers. No moisture in stratosphere.

The net radiation from each layer at night and also during day when the secant of the Sun's Zenith distance is 2 are given in Figs. 3, 4 and 5. In Fig. 3 alone, the case when sunlight is incident normally has also been included. As a limiting example, the values of radiation have also been calculated when the amount of moisture in the stratosphere is zero (see Fig. 6). In all the above cases, the stratosphere is supposed to lie above — 3, i. e. at a height of about 16 km as in the tropics.

Fig. 7 refers to the case when the temperature is uniformly 220° A above layer + 1; as usual, two values of humidity 100% and 25% are assumed for the troposphere and 25% for layers — 1 to — 3. .01 cm has been assumed to be the total moisture-content of the layers above — 3. Fig. 8 refers to temperature conditions such as exist on the average over Agra (India) during September and October [1].

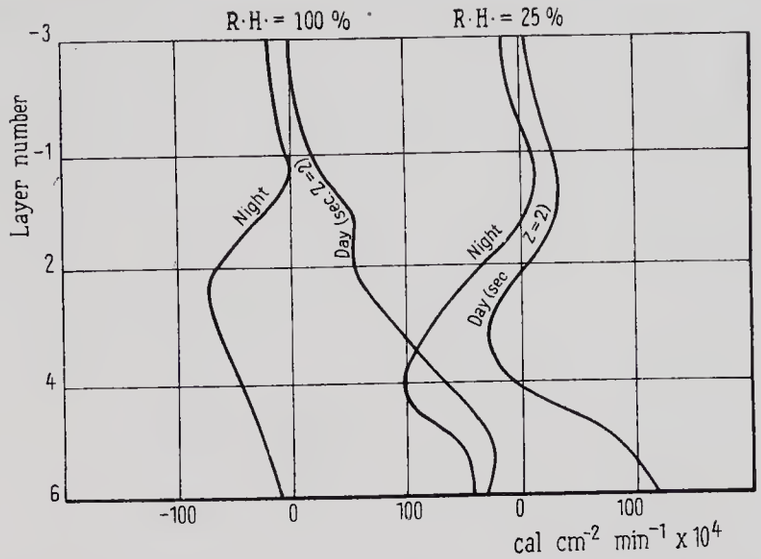

Fig. 7. Net rate of gain of energy by radiation by different atmospheric layers. Isothermal 220^0 A above + 1. Moisture above — 3. Assumed to be .01 cm.

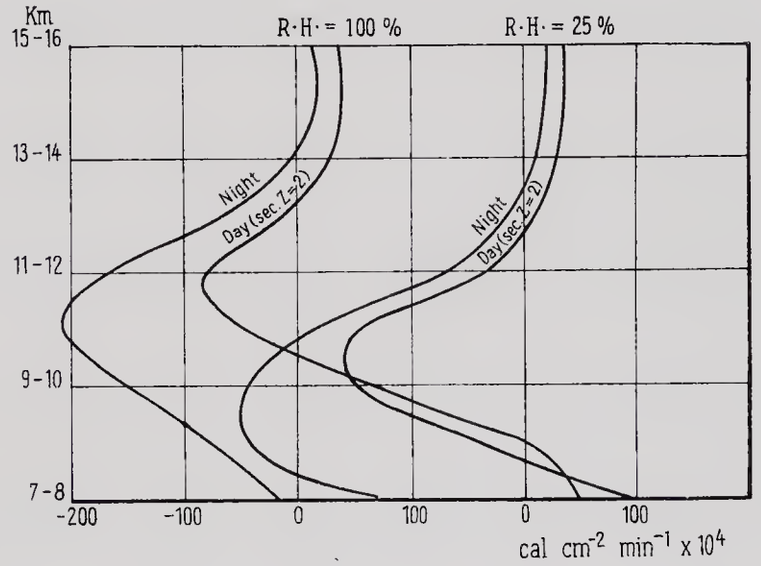

Fig. 8. Net rate of gain of energy by radiation by different layers of the atmosphere under mean N. India conditions in September and October — Moisture above — 3 assumed to be .0015 cm.

Discussion of results.

A very striking feature of the curve of atmospheric radiation which corresponds to 100% humidity in the troposphere in Fig. 3 is the large increase in the rate of loss energy as we go up from layer 6 to layer 2 or 1 and its rapid decrease at greater heights. The net loss of energy in layers 6 and — 3 are small. In the tropics, layers 6, + 1 and — 3 correspond to heights of about 8, 12 and 15 km respectively; in temperate latitudes, the corresponding heights are 2 to 3 km lower. When the effect of solar heating (with sun's rays incident at an angle of 60^0) is added, there is a net *gain* of energy up to layer + 2 and maximum net loss of energy in layers + 1 and — 1. When the angle of incidence is smaller, the heating is greater. Whether we consider day or night conditions they are

favourable for the increase of lapse-rate and eventually the development of instability and active convection in layers 5 to 1 — the intensity of instability and the maximum height of its extension being greater during day than during night. The convection may be expected to extend beyond — 1 and may go up even to — 3, i. e. practically to the upper limit of the region where there is a net loss of energy by radiation but the lapserate above 1 would be much less than in the layers immediately underneath. Fig. 3 (b) shows that a decrease of humidity in the troposphere from 100 to 25 per cent lowers the height of maximum loss of energy by about 2 km, but does not cause any other serious alteration in the character of the curves. Any super-saturation in the higher layers of the tropospherc will tend to raise the level of maximum cooling by radiation.

A comparison of Figures 3, 4, 5 and 6 shows that an increasc of moisture-content in the stratosphere produces the following effects:

(1) It lowers the height of the layer of maximum energy loss.
(2) It reduces the actual and differential cooling of the layers immediately below the above mentioned layer thus diminishing the tendency for the setting up of high lapse-rates in the lower layers, and
(3) When the moisture-content of the stratosphere is 0.01 cm or more, the effect of radiation is to increase the energy in the higher layers even during night.

Comparison of Figures 4 and 7 shows that when decrcase of temperature with height is assumed to stop above layer + 1, the rate of increase of energy in the layers — 1 to — 3 becomes smaller. The effect of substituting Agra conditions of temperature in the troposphere in September and October (Fig. 8) for those in Fig. 3 is to lower the layer of maximum energy loss but steepen the differential cooling of the layers.

We may also consider the actual rates of cooling. In Fig. 8 (a) the layer 10 to 11 km cools at the rate of 210×10^{-4} cal/cm^2/min when the sun is not shining. Taking the specific heat of air at constant pressure to be 0.242 and the mass of air over a square centimetre between 10 and 11 km to be 39 gms [Table 20 of (1)], the cooling of the layer in one hour of the night comes out to be 0.13° C or 1.6° C in 12 hrs. During day, with the sun at an altitude of 30°, the differential cooling of layer 11—12 km compared to 8—9 km is 0.16° C per hour. The fact that the maximum cooling during night hours is at a greater height than the maximum heating during day is of great importance in promoting increase of lapse-rate and not merely producing a slow settling down of the higher layers. Naturally, whenever extra warm air is introduced at heights of 7 to 9 km, it would lead to increased instability.

If we compare the curves of radiation given above with the height temperature curves in different parts of the world [Fig. 9 of (16)], the resemblance of the two sets of curves becomes very striking and strongly suggests that the difference between the nature of the transitions from troposphere to stratosphere in the tropics and temperate latitudes is due to thc different amounts of moisture present in the stratosphere. We have already seen that there are reasons to believe that there is less moisture present in the stratosphere in the tropics than in temperate latitudes.

Accepting as a hypothesis for the present that there is a moisture content of about 0.0015 cm in the tropical stratosphere, it is easy to see what will happen if the atmosphere is left to itself under the sole action of radiation. Let us take the case when the humidity in the troposphere is 100 %. Gradual increase of lapse-rate from 7 to 12 km will lead to mixing of air at different levels in the sub-stratosphere and condensation in levels like 3, 2 and 1. The result will be that some moisture will drop out as precipitation and by mixture with air at higher levels the air will get gradually drier and slowly tend to condition represented by 3 (b). The top part of sub-stratosphere will begin to get a net gain of heat instead of a loss and get absorbed into the stratosphere. The layer of maximum loss of heat due to radiation will also get lower and the minimum temperature reached correspondingly higher. More moisture will thus be able to pass into the stratosphere. We shall thus progress towards conditions represented by Fig. 4 (b) or even those of Fig. 7 (b) — where the differential cooling of layers is smaller and changes are generally more gradual. It seems therefore likely that the tropical stratosphere and sub-stratosphere when left to themselves under the sole action of radiation without further supplies of moisture from below would tend to get to the conditions of those of temperate latitudes.

Summary of reasons for the high level and low temperature of the tropical tropopause.

In the lower levels of the troposphere up to about 8 km the potential temperature over equatorial regions is higher than over temperate regions, and more important still, the moisture-content is greater. Owing to the increasing rate at which the vapour pressure of water increases with temperature, a lapse-rate of the environment which is stable for rising moist air at a lower temperature becomes unstable when the temperature is higher. At times when instability occurs, a greater quantity of moisture can be pushed upwards in tropical latitudes and convection extend to levels of lower temperatures than in temperate latitudes. Near the top of the water-vapour column, radiation produces another layer of large lapse-rate, which is higher the smaller the amount of moisture in the stratosphere. The cooling of the upper layers of the troposphere itself is the effective cause of reducing the amount of moisture penetrating into the stratosphere. These two circumstances therefore act and react on each other. A limit is reached to the possible cooling owing to the radiative action of carbon dioxide. Carbon dioxide being a less efficient absorber of atmospheric radiation than water-vapour, but possessing significant absorption for solar radiation, would have a higher equilibrium temperature than water-vapour. (Cf. Absorption of solar radiation between 2 and 3 μ and net loss of radiation between 13 and 16 μ in Tables 2, 3 and 4.) The continued increase of temperature from the tropopause to at least 25 km over the tropics may be attributed to this cause. But this point requires further investigation.

Meteorological office Poona 14/9/31.

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Upper Air Temperatures and Humidities in the Indian Peninsula

SINCE October 1928, more or less regular ascents of sounding balloons have been carried out from Poona and Hyderabad (Deccan) with meteorographs of the Dines type manufactured at the Upper Air Observatory, Agra. The ascents at Hyderabad were made from

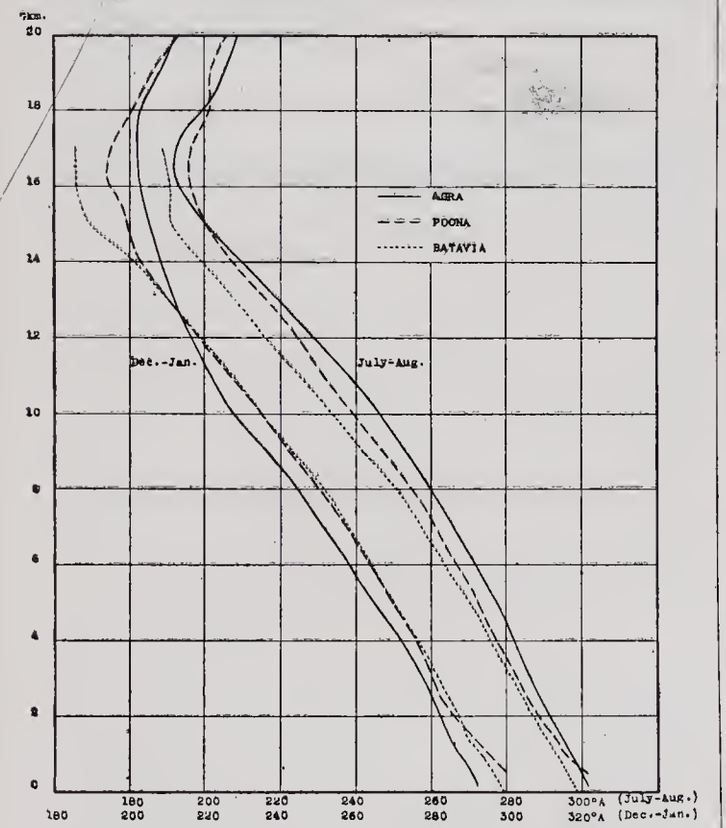

FIG. 1.—Upper air temperature over Agra, Poona, and Batavia.

the Nizamiah Observatory, Hyderabad, with the kind co-operation of its director. It may be of interest to summarise here some results of outstanding importance obtained as a result of these soundings.

(1) During the monsoon months, July and August, the atmosphere over the Deccan is invariably colder than that over Agra in northern India, up to a level of about 14 geodynamic kilometres—the maximum mean difference of temperature being 7° C. at a level of 10 gkm. Temperatures over Batavia in these months are lower still. The level of the tropopause in this season is about the same, or slightly lower, and its temperature higher in the Deccan than in northern India (Fig. 1). Considering the troposphere as a whole, the thermal equator over Indian longitudes lies over northern India at a latitude of about 25° N.

These results are specially interesting in view of the westerly to north-westerly movement of monsoon depressions. The normal upper winds are consistent with the temperature distribution.

During the months July-September, the relative humidity in the air over the Deccan generally shows a maximum (saturation) between 1·5 gkm. and 3·5 gkm., and is followed by a more or less rapid fall, extending over one or two kilometres, and at still higher levels by a rise. In about half the number of available records, the humidity falls off above 6-8 km., the fall being gradual. The decrease of humidity above the lower level of maximum humidity is sharper and larger during times of weak monsoon. It may be mentioned that the westerly winds of the monsoon give place to the easterlies of the inter-tropical circulation normally between 6 km. and 8 km.

(2) Conditions are markedly in contrast in the winter. In the period November-February, temperatures over northern India are lower than those over Poona up to 13 gkm., and above that level higher. Between 4 gkm. and 14 gkm., there is little difference between the temperatures over Batavia and Poona, but the tropopause is higher nearer the equator, and colder.

(3) The semi-permanent anticyclone in the upper air over the central parts of India during the months November-January shows itself in the temperatures over Poona as a well-marked region of small lapse-rate extending over 0·5-1 km., and starting at a level ranging from 2·5 km. to 3·5 km. The trajectories of air movement in the upper air show that the air below the inversion usually comes from the Punjab and northern Rajputana through east Central India and the Central Provinces; while above the inversion, the air supply is from a direction varying from north to west, and has, in general, a higher velocity. The air below the inversion is surface-heated continental air from higher latitudes, and has a high lapse-rate. As may be expected, there is a maximum of humidity at the top of the lower convective layer.

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No. 3260, VOL. 129]

Nature, 129, 615, 1932.

Distortion of the Tropopause due to Meridional Movements in the Sub-Stratosphere

In the neighbourhood of the equator, the height of the tropopause is about 17 gkm. and at latitude 70° N. about 10 gkm. The rate at which the height of the tropopause changes with latitude is, however, not uniform, the change being very rapid between 45° and 20° in winter, and between 50° and 30° in summer. The ring of cold air which collects near the tropopause over tropical latitudes will tend to spread out with a slight downward component towards higher latitudes. To compensate this movement, we may expect that there will be at lower levels a movement towards lower latitudes.

At the latitude of Agra (27° N.) in winter, the meridional variation of temperature is least at about 12 gkm., while at higher levels the temperature increases towards the pole and at lower levels towards the equator. The lower boundary of the spreading equatorial cold air will lie in the neighbourhood of 12 gkm. It is also known from pressure data that

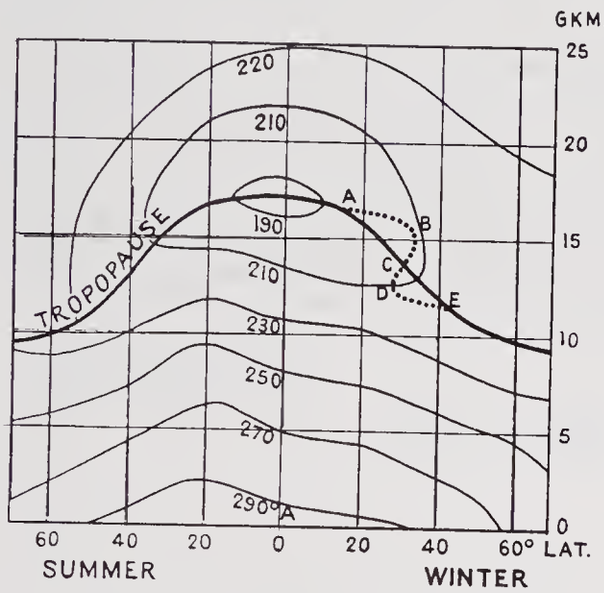

Fig. 1. Meridional distribution of temperature in the atmosphere over the northern hemisphere showing the tropopause and its distortion.

the westerly winds of the season in sub-tropical latitudes have their maximum strength at a height of 10–12 km. As an interesting consequence, it will follow that in the region of latitudes where there is a rapid variation of the height of the tropopause, it will often have a folded structure such as is represented by the dotted line in Fig. 1.

At Agra, in winter, the type of tropopause which occurs most frequently is one in which the transition from the troposphere to the stratosphere occurs in two stages, the lower one being at a height of 12–13 gkm., with the lapse-rate suddenly changing from a high to a low value, often reaching zero above the transition, and the second transition at a height of about 17 gkm., this being invariably an inversion. Immediately below the upper inversion, there is frequently a layer of positive lapse-rate with a mean value of 5° C. per km. of about 2 km. thickness.

This thermal structure is what one would expect if the lower transition corresponds to the tropopause of higher latitudes and the upper inversion transition to the tropopause of lower latitudes. Between these two, the air will be partly stratospheric air from higher latitudes and partly tropospheric air from lower latitudes. In summer, with the movement of the hump in the level of the tropopause towards higher latitudes, this folded structure of the tropopause is either absent at Agra, or if present, the difference of level between the transitions is very small.

At the latitude of Poona (18° N.), the double transitions are much less conspicuous than at Agra, though one can often notice them in winter and early summer. When present, the difference of level between the two transitions is smaller than at Agra, the lower one being at a height of about 14 gkm. and the upper at 16–17 gkm.

On the other hand, many of the temperature-height curves of places like Avalon (lat. 33° N.), Groesbeck (31° N.) and Fort Omaha (41° N.) in the United States[1] in summer show the double transition distinctly.

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Oct. 12.

[1] *Mon. Weather Rev.*, U.S.A., July 1914, May 1916, and June 1919; *Bulletin, Mount Weather Observatory*, 4, part 4, 1911.

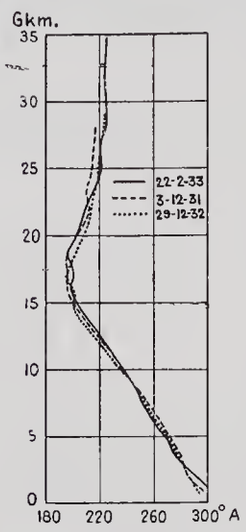
Nature, 132, 932, 1933.

Some Exceptionally High-Sounding Balloon Ascents at Poona and Temperatures in the Stratosphere over the Tropics.

DIRECT observations of temperature in the upper atmosphere above 25 km. are very scanty. From an analysis of temperatures obtained from sounding balloons in different parts of the world, it is known that at a height of about 25 km., temperature all over the earth is more or less uniform being about −55°C. Experiments on the reflection of explosive sounds from the upper atmosphere which have been carried out in recent years in Europe have led to the conclusion that temperature again rises to that near the ground at a height of about 40 km.

Special efforts at increasing the height reached by sounding balloons have been made by A. Wigand[1] of the Deutsche Seewarte, Hamburg, who has recorded five ascents which went above 25 km., the greatest height reached being 35·9 km. Wigand found that there was only a very small increase of temperature between 25 km. and 35 km., the value at the highest point being near −46°C.

The accompanying figure which gives the height-temperature curves obtained from three ascents made at Poona in 1931-33 shows that in the tropical stratosphere, the temperature goes on increasing with height up to about 30 gkm.[2] and that even at 34 gkm., there is no evidence of any large rise of temperature. All the ascents were made within one hour before sunset so that the top part of the records would have been traced after sunset and would not have been affected by inso ation. The temperature at the highest point was −49°C. No experiments have been made in the tropics on the reflection of sound waves from the stratosphere; but if it is assumed that the height of reflection is about the same as in temperate latitudes, the rate of rise of temperature should be very high immediately below the reflecting layer.



In a recent communication to *Nature*[3] Messrs. F. W. P. Götz, G. M. B. Dobson and A.R. Meetham have stated that observations at Arosa in Switzerland on the spectrum of the light received from the clear, blue zenith sky as the sun is rising or setting show that the average height of ozone there is about 20 km. which is much lower than the previously estimated heights (40-50 km). This conclusion gives support to the view[4] that the persistent rise of temperature between 18 and 25 km. in the tropical stratosphere is due to the presence of ozone. Attention may also be drawn to the fact that while in temperate latitudes, the temperature of the tropopause increases when its height lowers and *vice versa*, the height of the tropopause in the tropics does not show any tendency to rise above 17-18 km. in spite of large variations of temperature.[5]

The sounding balloons used in the above flights were made of 'Vulpro' tissue,[6] at the Upper Air Observatory, Agra.

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The Meteorological Office,
Poona,
November 7, 1933.

[1] A. Wigand, *Beitr. zur. Phys. der fr. Atmosphare*, **17**, p. 286, 1931.

[2] 1 gkm. at the latitude of Poona=1.021 km.

THE INDIAN SOUTHWEST MONSOON AND THE STRUCTURE OF DEPRESSIONS ASSOCIATED WITH IT.

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Introduction.

In a previous paper on the structure of two pre-monsoon storms in the Bay of Bengal[1] one of the authors and Mr. H. C. Banerjee have shown that surface-heated continental air entering the north-west of the Bay of Bengal, when it meets monsoon air, forms a " dry warm front " at which the continental air ascends over the monsoon air in the lower layers. It was also pointed out that owing to the difference in the lapse-rate between the two air masses, the dry warm front would, at levels higher than 3 km., transform itself into a " cold front ". Strong winds, heavy swell and fierce rain-squalls are experienced before this front within the monsoon air mass.

In the present paper, the general upper air circulation before and during the south-west monsoon with the attendant distribution of temperatures in the free atmosphere as far as can be gathered from the available data is discussed, followed by an analysis of two storms of the monsoon period. The principal features of the analysis are the use made of upper winds in tracing the sources of air supply and of detailed rainfall charts to elucidate the nature of the " fronts ". The rôle of the old monsoon air, as compared with that of surface-heated continental air in the storms which form at the head of the Bay in this season, is brought out.

A very good early summary of the mechanism of the south-west monsoon is contained in the Imperial Gazetteer of India, prepared out of material gathered by Sir John Eliot.[2] The subject has subsequently been discussed by various authors, notably by Simpson,[3] Harwood [4] and recently Wagner.[5] Some aspects of the question have also been considered by S. C. Roy and A. K. Roy [6] and by H. C. Banerjee and one of us.[7]

According to Simpson, the primary cause of the monsoon is the relatively high temperature and correspondingly low pressure over the land in the northern hemisphere during the summer. The air in the South Indian Ocean, under the influence of the

[1] K. R. Ramanathan and H. C. Banerjee : Ind. Met. Dept. Sc. Notes, Vol. IV, No. 34, 1931.

[2] The Imperial Gazetteer of India : Vol. I, Ch. III, 1907.

[3] G. C. Simpson, " The South-west Monsoon " : Q. J. R. Met. Soc., Vol. 47, p. 151, 1921.

[4] W. A. Harwood, " Upper air movement in the Indian Monsoons, etc." : Mem. Ind. Met. Dept., Vol. XXIV, Part 8, p. 249, 1921.

[5] A. Wagner, Zur Aerologie des Indischen Monsuns : Ger. Beitr. z. Geophy., Bd. 30, p. 196, 1931.

[6] S. C. Roy and A. K. Roy, " Structure and Movement of Cyclones in the Indian Seas " : Beitr. zur Physik der freien Atmosph., Bd. 16, p. 224, 1930.

[7] H. C. Banerjee and K. R. Ramanathan, " Upper Air Circulation over India and the neighbourhood, etc." : Ind. Met. Dept. Sc. Notes, Vol. III, No. 21, 1930.

Mem. Ind. Met. Dept 26(2), 13–36, 1933.

pressure distribution and of the rotation of the earth, moves to the north-west in the southern hemisphere and to the north-east in the northern. The moist air with its long sea-travel is caught by the mountain system of India and the rainfall is determined by the ranges of mountains in and around India. The small rainfall in the north-west of India is explained by Simpson as being due to the arrangement of the neighbouring mountains and the prevalence of a dry upper wind and the high temperature. Simpson does not discuss the depressions of the monsoon season and their importance as agencies responsible for precipitation over a considerable part of the country. Harwood discusses the circulation in the upper levels and the manner in which the air brought into India by the lower monsoon currents is disposed of. He concludes that of this air :—

(*a*) " Part crosses the Himalayas and the mountains of north-east India and is then lost sight of but may be presumed to continue as part of the circulation round the Asiatic ' low '.

(*b*) Part rises and passes first westwards and then northwards round the western side of a high pressure area in the upper levels over north India.

(*c*) Part rises and passes westwards, subsequently descending to rejoin the lower monsoon current over the Arabian Sea ; and

(*d*) Part rises and passes first westwards and then southwards in the same way as the anti-monsoon postulated by Blanford and Eliot."

Harwood does not consider the distribution of rainfall or the causes which give rise to it.

Wagner,[5] in an important paper, has emphasised the view that the south-west monsoon represents a stationary system of cyclonic disturbances reaching up to the average height of the Himalayas between two air-masses, one continental belonging to the W. winds of the middle latitudes and the other maritime. He considers that the continental air is warmer than the monsoon air at the surface and up to 1 km. and colder above and that a considerable part of the monsoon precipitation in and south of the Gangetic plain is due to cyclonic convergence. Wagner's stream-lines are drawn with mean wind data for the months June, July and August. For heights above 3 kms., the data of one single year, 1928, have been used for 13 stations. As Wagner himself points out, June cannot be considered a representative monsoon month for a considerable part of north India. The present paper contains a discussion of average monthly upper air stream-lines and temperatures before and during the monsoon * and an analysis of two typical monsoon depressions during the months June and July, 1930.

We shall first examine the mean monthly stream-lines (at 1, 2, 3, 4, 6 and 8 km.) and isotherms (as far as can be made out from the available data) at different heights in the months May, June and July.

SECTION I.

Normal wind and temperature distribution in May, June and July.

Wind-roses at a number of pilot balloon stations and approximate isobars at 0·5, 1, 2 and 3 km. have been published in the departmental Scientific Note, Vol. 1, No. 8. Up-to-date average upper wind velocities for different levels have also been recently calculated, utilising data at more stations—and the charts for May prepared with them are reproduced in *Figures 1-6*. In drawing conclusions, these average stream-lines should be

[5] A. Wagner, *Loc. cit.*

* A more detailed study of the mean monthly stream-lines and the general circulation in the Indian area is in progress.

considered along with charts of wind-roses both of pilot balloon winds and of cloud movement. They bring out the following facts :—

May.

At 0·5 and 1 km. the winds are westerly to north-westerly over most of the Arabian Sea and the whole of India west of a line running from Cape Camorin to between Allahabad and Patna ; east of this line the winds are westerly to south-westerly. While over the north Indian plains, the air is surface-heated continental air, further south it should be considered as maritime continental air, the length of sea travel increasing both in the Arabian Sea and the Bay of Bengal with decrease of latitude and increase of longitude. At 2 km. the north-westerly continental current extends much further towards the south-east, the line of separation between continental and maritime air lying now in the Bay of Bengal between east Ceylon and south of the Pegu Coast in Burma. Although the mean wind at Port Blair is weak, this is due more to the variability of the wind direction than to general weakness of wind, both westerlies to south-westerlies and easterlies and south-easterlies being common. The region of separation of continental and maritime air at 2 km. coincides more or less with the region where storms originate or strengthen in the Bay of Bengal.[8] The maritime air pushes itself farthest northwards in the east of the Bay of Bengal. The normal winds at 2, 3, 4 and 6 km. indicate that while the continental air at 3 km. pushes itself further southward than at 2 km., at 4 and 6 km. it is pushed backward towards the north by maritime air. This is in agreement with the scheme sketched out in *Fig. 27* of " Scientific Notes ", Vol. IV, No. 34.

Some light is thrown on the mechanism of the change of wind with height by considering the distribution of temperature in the upper air. In *Figs. 19-21* are shown the monthly mean temperatures at 2, 3, 4 km. in May, June and July at a number of stations, the values being based on results of sounding balloon ascents, aeroplane ascents and mountain observations. Sounding balloon ascents were made at about the time of sunset, aeroplane data refer to forenoon hours (9 to 12 hours) and mountain observations to 8 hours local time. The number of observations and period over which they extend are also different. The isotherms that have been drawn can therefore be considered only as tentative. They have, however, an internal consistency which justifies our drawing general conclusions. In May the isotherms at 2 km. have a great similarity to the isotherms at the surface. At 3 km. there seems to be little difference of temperature between the different parts of India with the possible exception that N. E. India may be slightly cooler by 1° or 2°. The southing of winds in the Bay of Bengal, Burma and N. E. India is obviously due to the low pressure at the surface in the Deccan and the central parts of the country caused by the heating of the land area. The marked change in the wind circulation at 2 and 3 km. compared with that at 1 km. indicates a greater decrease of pressure with height and a correspondingly lower temperature in the Bay than in the Peninsula and the corresponding northward extension of maritime air in the Bay of Bengal above 2 km. is therefore a consequence primarily of the differential heating of the Peninsula and the Bay.

June.

The main points of difference in the wind system of June (*Figs. 7-12*) at 1 and 2 km. as compared with that of May are the more marked westing and strengthening of winds

[8] C. W. B. Normand, " Storm Tracks in the Bay of Bengal ", Ind. Met. Dept., 1925.

in the Arabian Sea and the Peninsula and their increased southing and strengthening in the Bay of Bengal and Burma. The approximate line of meeting of surface-heated land air and of fresh sea air at 2 km. in the Bay of Bengal has naturally got shifted northwards and the Arakan hills have exerted their influence in rendering the line of discontinuity in the Bay nearly south to north. The weakness of wind at Aden at this level with the contrasted winds at 1 and 3 km. indicates a level of transition at about 2 km. At 3 km. the winds in South India and the Bay of Bengal have weakened and those in the north of the Peninsula, on the Mekran Coast and at Aden have acquired a more northerly character. While caution is necessary in interpreting the former result as there will be a tendency to miss out days of stronger wind owing to the absence of pilot balloon information, we may be practically certain about the latter, as a comparison of the number of observations will show. The winds at 4 km. are more or less similar to those at 3 km. and both of these show that the winds of northerly origin overspread those of more southerly origin in the middle of the Peninsula. The winds at 6 km. are very weak in the south of the Peninsula and have no defined direction. This is also borne out by observations of middle cloud. The advance of southerly to south-easterly current in Bengal at 6 km. over the north-westerly current at 4 km. shows that the former stream now behaves as warmer air. The resultant movement, however, is weak. At 8 km. the general upper easterly circulation has set in over the south and the ridge of high pressure separating the easterly and westerly circulations now lies over a latitude of about 22° North showing a northward shift of more than 10° since May. It will be noticed that except for the first 2 km. the winds in the Arabian Sea are from a northerly direction, those in Burma and a great part of the Bay of Bengal are from the south.

Considering the distribution of temperature, while in May at 2 km. the decrease of temperature towards the north persists in the Gangetic Valley, the gradient being roughly perpendicular to the Himalayas, it has become much weaker in June (*Fig. 20*). The region of highest temperature has also got shifted from the central parts of the country north-westwards to Rajputana and Sind. The horizontal temperature gradients at 2 km. have become generally weaker. The level of approximate equality of temperature in different parts of the country is in this month at about 4 km.

July.

As representing conditions at the time when India is under the full sway of the monsoon, the distribution of winds and temperature in July are particularly interesting (*Figs. 13-18*).

The main point of difference in the wind systems at 1 and 2 km. between June and July is the incursion of south-easterly winds in the Gangetic Valley right up to the Punjab Hills. With the turning round of the maritime winds along the Himalayas towards the north-west the continental air sector at 2 km. becomes very much restricted in area and in the region between Gujarat and Orissa to some extent loses its individuality owing to the supply of moisture from below and sideways from both south and north-east ; it becomes the mixed monsoon air of S. C. Roy and A. K. Roy. The southern boundary of this region is extremely indefinite.* Pure continental air exists only to the west of Rajputana. It is worthy of note that the wind at Aden is in this month from the west-

* Wagner says that the surface of separation between the continental air and the SW monsoon air is sharply pronounced at 2 and 3 km. This difference is due to his averaging the data for June, July and August.

south-west unlike the weak north-easterly of the previous month. At 3 and 4 km. " the continental air " has spread over a larger area in the Peninsula. In the south of the Peninsula the air is probably purely of maritime origin but in the middle of the Peninsula, there should be a high frequency of occasions when the air at these levels is of continental origin. Comparing the wind directions at the pilot balloon stations in Baluchistan, Persia and Arabia at 2, 3 and 4 km. it appears that the continental air pushes farthest into the Arabian Sea at 3 km.

Even at 4 km. the air supply over the north and west Arabian Sea has begun to be replenished by air over the Gangetic Valley, while at 6 km. the easterlies are in full sway over North India and the winds are very weak in the Peninsula. The contrast of conditions at 6 km. between June and July is very striking, the line of separation between continental and maritime air which lay over the north Bay of Bengal having been displaced to the Punjab and Kashmir. At 8 km. the system of circulation has again assumed a simple form similar to that in June, but with the high pressure ridge displaced northwards by another 8°.

The upper air temperatures (*Fig. 21*) show that the region of highest temperature at 2 and 3 km. is now Baluchistan and Persia. The air over South India is definitely cooler than that over North India as will be seen from a comparison of temperatures at Agra, Hyderabad and Kodaikanal. This is shown more conspicuously by the mean monthly tephigrams and dew-point temperature diagrams for July of the air over Hyderabad and Agra obtained from results of sounding balloon ascents (*Fig. 22*). The upper air data of individual days also, whenever they are available, bear this out.

The increase of temperature of the air in going from the Peninsula to North India is due to the following causes. When the moist air reaches the Western Ghats as a cold air mass at the surface orographic precipitation results, causing an increase of temperature above the low-cloud level and a decrease below. The Deccan Tableland which is swept by the westerly subsiding winds is generally free from heavy rain and the air, even right down to the surface, gets warmed by insolation. On entering the Bay of Bengal, more moisture is picked up and with renewed precipitation on the Burmese Coast the upper air gets warmed up further. The easterly current over the Gangetic Plain is, above 6 km., part of the general easterly circulation, but this stream is fed from the south by air rising over the Bay and Burma and by a similar addition from the east by the air rising over the region of the Chinese monsoon. Absorption of solar radiation by the water vapour in the atmosphere with the long hours of sunshine and the sun practically overhead at noon is also an important cause of increasing the temperature. While the easterly current is generally not fully saturated, it has a larger amount of moisture throughout its thickness, and owing to the high temperature, the absolute amount of moisture held is large. Old monsoon air may therefore be expected to behave as a warm air mass when compared with fresh monsoon air.

It will also show a similar behaviour towards surface-heated continental air above a level which may vary from 2 to 4 km.

SECTION II.

We shall now examine in some detail the air movement and precipitation connected with two depressions during the monsoon of 1930. Short general descriptions of these have been published in Part C of the India Weather Review for 1930.

It may be mentioned at the outset that the upper air trajectories at different levels have been drawn with the aid of winds obtained from pilot balloon observations. The observations are made twice daily, once in the morning and once in the afternoon at North Indian Stations and only in the morning at stations in the Deccan. In times of disturbed weather, however, single flight stations also take two observations a day. The trajectories have been drawn giving due consideration to the general wind field. It has been assumed that the level of the air does not change during its travel; this is obviously not correct, but owing to the absence of data which will enable us to fix the isentropic surfaces' no better method is available.

The depression during the period 27th June to 4th July, 1930.

The upper winds over the Indian area on the morning of the 27th June 1930 had a remarkably simple structure. In the Indian Peninsula, approximately south of latitude 21°, the winds were westerly up to at least 3 km., while north of this latitude they were practically easterly over most of north India and the Mekran Coast. On the Arakan Coast in Burma, the winds were south-south-easterly to south-easterly up to 2 km. and tended to become easterly at higher levels. The winds at 1, 2 and 3 km. are shown in *Figure 23.*

The following points are noteworthy :—

(1) At 1 km. the wind at Rangoon is WSW, while at Akyab and Chittagong it is SSE. This is due to the Arakan Yomas and the Chin Hills deflecting the westerly current northward. There is a similar though weaker tendency at Ahmedabad, due to the effect of the Central Indian plateau and the Aravalli hills.

(2) In Gujarat, Sind and the Mekran Coasts the strength of the easterly winds generally increased with height up to 6 km. The easterly current at Agra extended up to 20 km.

This system of wind circulation was associated with abnormal excess of pressure north of a line running approximately from Lat. 25° N., Long. 65° E. to Lat. 17° N., Long. 95° E.

Ships' observations in the Arabian Sea show that on the 27th morning strong south-westerly or west-south-westerly winds extended up to about 20° N.

An extraordinary strengthening of upper winds took place in the Deccan between the 26th and the 27th. This is well brought out from the wind data of Hyderabad.

TABLE 1.

Date and time.		Height above sea level in km.						
		1·0	1·5	2·0	2·5	3·0	4·0	5·0
26th June, 1930 (07-13)	Direction	265°	290°	290°	315°	335°	290°	295°
	Vel. m. p. s.	13·0	14·0	10·5	3·0	2·0	5·0	6·0
27th June, 1930 (06-55)	Direction	260°	265°	280°	280°	280°	..	..
	Vel. m. p. s.	19·5	18·5	18·0	15·5	14·5	..	..

Directions are in degrees from north in a clock-wise direction and velocitics in metres per second.

This rapid strengthening of wind produced a short-lived shallow low-pressure area between the Satpuras and the Vindhyas near Latitude 22° N., Long. 76° E. and a ridge of high pressure down the Peninsula. All along the line of separation of westerly and easterly wind-systems, there was this tendency for the formation of cyclonic vortices, but further development took place in places where orographical features were favourable for the continuous creation of cyclonic vorticity and contrasted air masses could converge. The morning weather chart of 28th June 1930 shows the development of a low pressure area in the north-east corner of the Arabian Sea off Kathiawar (*Fig. 24a*). (In these weather charts, winds over land at 0·5 km. above sea level obtained from pilot balloon ascents are shown by full-lined arrows.) Surface winds over the sea and high level stations are also shown by continuous arrows, and those at ground level (at a few representative stations) by discontinuous ones. From *Fig. 24a* and the accompanying chart of upper air trajectories (*Fig. 24b*) it will be seen that while at 1 km. the south-westerly winds were deflected northwards and then westwards into Gujarat, lower Sind and the Mekran Coast, winds at 2 km. and above over Karachi and Gwador had a northerly land origin. The upper winds at Karachi and Gwador on the morning of 28th June 1930 are given in *Table 2.*

TABLE 2.

Place.	Date and time.		Height in km. above sea level.					
			0·5	1·0	1·5	2·0	2·5	3·0
Karachi .	28th June, 1930 (06-23)	Direction .	70	105	110	95	80	70
		Vel. m. p. s. .	5·5	5·0	9·0	13·0	13·5	15·0
Gwador .	28th June, 1930 (07-09)	Direction .	185	80	360	35	40	35
		Vel. m. p. s. .	4·0	9·0	9·0	13·0	20·0	24·0

The surface temperatures at Karachi and in Gujarat were of the order of 84° F. while further north in north-west India, they varied from 94° to 100° F. The over-running of the moist south-westerly winds by the drier and warmer (at the surface) land air such as is indicated by the backing of the winds at Karachi and Gwador can only lead to a strong inversion of the type usually observed at Karachi in this season. It is only when the monsoon air is sufficiently thick that the difference of lapse rates between the monsoon air and the dry land air can lead to the disappearance of the inversion and, under favourable conditions of air movement, cause instability.

The southward deflection of air currents at 1 and 2 km. at Sambalpur and Waltair is a necessary consequence of the northward forced movement of air on the Burma Coast. In *Fig. 24b* is also given the areas of general rainfall during the *next* 24 hours. In determining these areas, use has been made of the rainfall data of all raingauge stations* in the country. Areas which had a general rainfall of 4″ and over in 24 hours are shaded black, those with rainfall between 2″ and 4″ by vertical hatching and those with falls between 2″ and 0·5″ by dots. Areas with scattered light falls have not been marked. The

* There are about 3,300 stations in India and Burma registering rainfall.

moderately heavy rainfall during the next 24 hours was confined to the coastal strip on the west coast of the Peninsula and to a small area on the Orissa coast. Rainfall was practically confined to south of Lat. 24° N. The two regions of comparative freedom from rainfall, one in the west Central Provinces and the other in west Bengal and Orissa, were regions of divergence. Places which reported thunder or lightning are also marked in the figure.

On the 29th morning, the Arabian Sea depression had moved north-westwards and another depression had also developed in the Bay of Bengal near Lat. 19° N., Long. 86½° E. (*Fig. 25a*). The simple upper wind system of the 27th morning had become very much disturbed. The principal new feature was an incursion of northerly to north-westerly upper winds in the North-West Frontier Province and the Punjab. In connection with the Bay depression the transitional zone between about Lat. 19° N., Long. 86° E. and Lat. 23° N., Long. 80° E., was being contracted to a front, the thickness of the current from the Arabian Sea increasing with decrease of latitude. At this front, the north-easterly deflected or old monsoon air was meeting the westerly to north-westerly Arabian Sea monsoon current broadside on. The upper winds at Jubbulpore and the rainfall during the next 24 hours (*Fig. 25b*) show that at this place the old monsoon air at 2 to 4 km. was passing over fresh monsoon air. The area of heavy rainfall on the Northern Circars and Orissa Coast was due to convergence of the very fast monsoon current with the northerly deflected monsoon current, aided by the action of the hills near the Circars Coast in stemming the main monsoon current. It will be noticed that there was a patch of precipitation in Rajputana on and to the west of the Aravallis which was obviously due to the deflected Arabian Sea current overrun by easterly winds. A new feature is the area of precipitation in the south-east Punjab and the west United Provinces with locally heavy falls. The trajectories show that this was due to the obstruction set up against the easterly current by a north-westerly and northerly current in the Punjab which was specially marked at 2 to 4 km. and whose onset should be considered as induced by the rapid deflection of the easterly current round the low pressure areas in the Bay of Bengal and the Arabian Sea. Practically all rainfall north of Lat. 20° N. was attended with thunder or lightning.

On the 30th morning, the storm in the Bay had concentrated without any appreciable movement (*Figs. 26a* and *26b*). The up-glide surface associated with it shows little displacement since the previous morning. Some extracts from the logs of S. S. Badarpur and S. S. Mathura are reproduced in *Tables 3* and *4* below, which show that the front extended out to sea and that no particularly severe weather was experienced near the centre of low pressure. They also show clearly the nature of weather experienced in the neighbourhood of such a front.

TABLE 3.

Log of S. S. Badarpur.

Date.	Time (Hrs.)	Lat. (N.)	Long. (E.)	Bar. (Inches.)	Air Temp. (°F.)	Cloud.	Wind (Beaufort scale).	Weather Remarks.
		° ′	° ′					
29th June, 1930	4	14 05	81 31	29·58	82	St 10	WSW 3	Overcast with drizzling rain.
	8	14 38	82 07	·60	83	St 10	WNW 5	Overcast.
	12	15 12	82 43	·55	83	St 10	WNW 6	Overcast with frequent light rain squalls.
	16	15 46	83 19	·43	80	Nb 10	W/N 6/7	Hard squalls with light rain but clear intervals.
	20	16 20	83 55	·40	82	St 10	W 7	Fierce squalls with heavy rain but clear intervals.
	24	16 54	84 31	·35	81	Ci-St, St, Nb } 10	W/S 7	Frequent fierce squalls getting harder and intervals decreasing. No rain or lightning.
30th June, 1930	4	17 28	85 07	·25	80	Nb, St } 10	WSW 8	Squalls almost continuous. Wind increasing to gale force. Some light rain in squalls but horizon clear in intervals.
	8	18 01	85 43	·24	80	Do.	SW/W 6	Similar weather continued till 06-30 when the first heavy rain fell during a squall. Heavy rain continued but wind ceased off a bit.
	10	..	..	·18	81	Ci-Cu, Nb, St } 9	SW/W 6	Frequent heavy rain continued, but squalls less frequent. Small patches of blue sky appeared at 10.

TABLE 3—*contd.*

Log of S. S. Badarpur.

Date.	Time (Hrs.)	Lat. (N.)	Long. (E.)	Bar. (Inches.)	Air Temp. (°F.)	Cloud.	Wind. (Beaufort scale).	Weather Remarks.
		° ′	° ′					
30th June, 1930 —*contd.*	12	18 35	86 19	29·16	81	Ci-Cu, S-Cu, St-Nb } 10	SW 6	10-30 to 11-45 continuous and heavy rain. 12-00 sky clearing.
	14	..	..	·14	82	Ci-Cu, St-Cu } 7/8	SW 6	Occasional light rain showers. Weather rapidly clearing and becoming fine and clear, but barometer still falling.
	17	..	..	·14	84	Ci-Cu, Nb, Cu } 6	S 5/4	Short hard rain squall at 17 hours. Passing showers before.
	18	..	..	·17	83	..	SSE 4	Fine and clear.
	20	18 44	87 22	·22	83	Cu-Nb, Nb-S } 5	SE 6	Sky clear overhead but heavy rain lying down southward.

The ship must have passed nearest the centre at about 10 hours on the 30th. Note the mildness of weather on the eastern and northern sides and absence of thunder or lightning even on the night of the 29th. The transition from south-westerly to south-easterly wind was rapid and although attended with a short rain squall, was not attended with very severe weather. Between 20 and 24 hours it was fine and clear with occasional light rain squalls.

Table 4.

Log of S. S. Mathura.

Date.	Time. (Hrs.)	Lat. (N.)	Long. (E.)	Bar. (Inches.)	Air Temp. (°F.)	Wind (Beaufort scale).	Weather Remarks.
		° ′	° ′				
30th June, 1930 .	8	17 21	84 54	29·30	80	W/S 6	Heavy rain.
	12	17 56	85 34	·21	81	WSW 6/7	Rain squalls.
	14	18 18	85 56	·10	81	SSW 5	
	15	18 29	86 08	·07	82	NW/N 3	
	16	18 37	86 16	·07	82	N 3	
	17	18 45	86 24	·05	84	SW 2	
	18	18 53	86 32	·07	84	SW 3	
	20	19 08	86 48	·13	83	E 4	Dull.
	22	19 32	87 02	·23	83	ESE 5	
	24	20 06	87 13	·20	83	SE 5	Frequent rain squalls.

The ship passed very near the centre of the storm at about 17 hours. Note the increase of temperature near the " calm " centre and the heavy rain in the south-west.

The upper air trajectories in *Fig. 26b* show that at this " warm " front, the participating air masses were the fresh monsoon air and deflected monsoon air mixed with air from Siam and Indo-China. The directions of the air currents, the variation of wind with height at Jubbulpore and the distribution of rainfall during the next 24 hours all bear out this conclusion. At such a surface, with the orientation existing at 8 hours on 30th June 1930 the warm air will, as is well-known, be accelerated north-westwards and the cold air south-eastwards. Naturally, the tendency will be for the depression to move north-westwards. The heavy rainfall area from Raipur to Calingapatam can with confidence be extended out to sea up to Lat. 18½° N., Long. 86° E. Jubbulpore and Waltair winds are given below in *Table 5*.

TABLE 5.

Place, date and time.		Height above sea-level.						
Jubbulpore.		0·6 km.	0·9 km.	1·5 km.	2·0 km.	3·0 km.	4·0 km.	4·5 km.
30th June 1930 (06-43) .	Direction .	285°	335°	70°	65°	80°	65°	60°
	Vel. m. p. s.	6·0	6·0	5·0	6·5	12·0	12·5	[13·0
Waltair.		0·5 km.	1·0 km.	1·5 km.				
30th June 1930 (08-41) .	Direction .	270°	310°	340°	..	..	..	..
	Vel. m. p. s. .	13·0	9·0	11·5	..	..	..	..

The upper air trajectories also make it clear that the heavy rainfall on the Gujarat Coast was due to the deflected monsoon air rising over the fresh monsoon air from the Arabian Sea. It may be noted that the latitude at which heavy rainfall commenced on the Arabian Sea Coast was about the same as that at which it ended in the east Central Provinces. On the morning of the 1st July, the Arabian Sea depression had entered land and was being dissipated (*Fig. 27a*) ; this helped to divert the monsoon air that was feeding into this depression to flow eastward. In *Fig. 27b* is also drawn with the help of pilot balloon winds and movements of low clouds, the line of separation at 2 km. between the Arabian Sea monsoon air and the deflected monsoon air. The position of this line with respect to the area of heavy rainfall during the next 24 hours shows that the rainfall was mainly in the fresh monsoon air sector. The importance of convergence of deep fresh monsoon air and old monsoon air for producing heavy and extensive precipitation is again evident. The entry of old monsoon air up to 2 km. on the Mekran Coast with pure continental air above caused extension of precipitation into that area.

The surface chart on 2nd July 1930 (*Fig. 28a*) shows an interposition of a north-westerly current between the north-easterly deflected monsoon current and the westerly fresh monsoon current. The deflected monsoon air was ascending over the intervening shallow north-westerly air and as is evident from *Fig. 28b* heavy precipitation began where the fresh monsoon air of sufficient thickness (more than 2 km.) was encountered. The low cloud directions at Neemuch, Hoshangabad, Amraoti and Jagdalpur were westerly while at Saugor and Raipur, they were northerly. At Chanda, it was southerly. Surface temperatures were lowest in the region of westerly currents. It is noteworthy that the north-easterly current at Sambalpur (Lat. 21° 28′ N., Long. 84° 01′ E.) did not cause

heavy rainfall further south-west where it met the monsoon current ; this was due to the facts (1) that the fresh monsoon current was deflected south-eastwards owing to the action of the front between Hoshangabad and Chanda and could not therefore form an effective obstacle in the path of the north-easterly deflected monsoon current and (2) that the Arabian Sea current had already had its moisture decreased in its lower layers and increased in its upper layers owing to the heavy rainfall within it on the previous day and had thus become similar in properties to old monsoon air. The effect of the front is well seen in the pilot balloon winds at Hyderabad and Waltair which were very strong WNW to NW at 1·5 and 2 km, *Table 6*.

TABLE 6.

Place, date and time.		Height above sea-level in km.				
		0·5	1·0	1·5	2·0	2·5
Hyderabad.						
2nd July, 1930 (07-20) . . .	Direction .	..	215	295	300	..
	Vel. m. p. s. .	..	22·0	27·0	30·0	..
Waltair.						
2nd July, 1930 (14-50) . . .	Direction .	265	270	290	300	305
	Vel. m. p. s. .	15·0	12·0	21·5	17·0	23·0

The air from Bengal having been deflected south-westward, NW Indian air began to be drawn in above 2 km. into Rajputana and Central India as shown by the upper wind trajectories at Ajmer and Agra (*Fig. 28b*). Comparison of the heavy rainfall chart with a contour map shows that the very heavy rainfall in the Central Provinces was concentrated in the Narbada Valley and in the Purna and Wardha valleys respectively. The divergence of south-westerly winds in north Bombay and Gujarat, one branch going up the Narbada valley and the other to the angle formed between the Aravallis and the west Central Indian Hills, is of frequent occurrence during the monsoon ; the heavy rainfall area in Central India was due to the convergence of the south-westerly and northerly winds at the Central Indian Hills. In the surface chart of 3rd July 1930 (*Fig. 29a*), the temperature of air at the surface reduced to sea level assuming a uniform lapse-rate of 6° C. per km. has also been shown, as an example. The higher temperature of the north-easterly air and the marked cooling of the shallow north-westerly current within the area of rainfall are evident. The double branch of the area of heavy rainfall during the next 24 hours (*Fig. 29b*) is accounted for by the influence of the Aravallis and Central Indian Hills in promoting convergence and deflecting the monsoon current. Owing to the absence of upper wind information, it is not possible to be definite about what took place at the heavy rainfall area in Gujarat, but presumably a moist surface layer not less than 2 km. thick had superposed on it drier north-westerly air at 3 and 4 km. and higher still north-easterly old monsoon air. Limited instability between the top of the fresh monsoon air and bottom of the old monsoon air would then occur, the source of supply of moisture for the heavy rainfall being mainly the fresh monsoon air at the surface. The low temperatures of both dry and wet bulbs at the surface after rainfall would be caused by mixing with air of less specific humidity at levels above 2 km.

On the 4th morning, the low pressure area was diffuse with centre between Jhansi and Gwalior (*Fig. 30*). The front between the fresh monsoon air and deflected monsoon air had disappeared. By next morning the depression had become still more diffuse and moved north-eastwards between Mainpuri and Cawnpore where it broke up. It is not, however, necessary to pursue the matter further. The distribution of reduced wet bulb temperature (reduced to mean sea level on the assumption that it follows the curve of saturation adiabatic)—*Fig. 31*—shows that the old monsoon air had a greater heat content at the surface.

SECTION III.

The depression of the period 13th to 23rd July, 1930.

Following the decay of the monsoon depression on the eastern side of the Aravalli between the 10th and the 11th July 1930, practically the whole of the Deccan became filled with air of continental origin at 2 and 3 km. on the 13th (*Fig. 32*). As Upper Burma and north-east India were also under the influence of westerly winds of either land origin or air which though originally coming from the sea had for some days lain over land, the rainfall over the country was confined to afternoon instability showers usually attended with thunder. The only exceptions were the Arakan and Pegu Coasts in Burma where maritime winds of 2 to 3 km. thickness were causing moderately heavy precipitation along the coastal strip. The same figure shows the areas of general rainfall during the next 24 hours.

14th July, 1930.

On the morning of the 14th the upper wind directions above 2 km. at Madras, Hyderabad and Waltair showed a marked change from some north-westerly to a westerly or west-south-westerly direction. The following table gives the directions and velocities of upper winds at Madras, Hyderabad and Waltair on the dates 13th to 17th.

TABLE 7.

Date.	Time.		Height in km.						
			0·5	1·0	2·0	3·0	4·0	5·0	6·0
Madras.	Hrs.								
13th July, 1930 .	07 14	Direction .	280	325	315	330	305	..	..
		Vel. m. p. s. .	10·5	6·5	4·5	6·5	4·5	..	..
14th July, 1930 .	07 53	Direction .	285	305	260	255	225	250	240
		Vel. m. p. s. .	10·0	7·0	6·5	6·5	6·0	5·0	7·0
15th July, 1930 .	07 21	Direction .	280	300	270	270	..	..	..
		Vel. m. p. s. .	6·5	8·5	6·5	9·5	..	..	..
16th July, 1930 .	07 58	Direction .	275	295	290	280	280	..	..
		Vel. m. p. s. .	12·0	14·0	7·5	11·0	11·0	..	..
17th July, 1930 .	07 45	Direction .	260	275	300	295	..	..	..
		Vel. m. p. s. .	17·0	19·5	10·5	9·0	..	..	..

TABLE 7—*contd.*

Date.	Time.		Height in km.						
				1·0	2·0	3·0	4·0	5·0	6·0
Hyderabad.	Hrs.		(0·76 km.)						
13th July, 1930 .	07 17	Direction .	295	310	310	..	..	..	..
		Vel. m. p. s. .	13·5	15·0	12·5	..	..	..	..
14th July, 1930 .	07 47	Direction .	280	290	285	250	..	..	..
		Vel. m. p. s. .	7·0	11·5	11·5	10·5	..	..	..
15th July, 1930 .	07 34	Direction .	280	295	295	280	..	..	..
		Vel. m. p. s. .	11·0	14·0	14·0	10·0	..	..	..
16th July, 1930 .	07 28	Direction .	270	270	290	290	..	..	..
		Vel. m. p. s. .	14·0	15·0	21·5	16·5	..	..	..
17th July, 1930 .	08 39	Direction .	255	260	..	..	..	..	..
		Vel. m. p. s. .	11·5	14·5	..	..	..	..	..
Waltair.	Hrs.		(0·5 km.)						
13th July, 1930 .	07 26	Direction .	280	320	305	300	..	..	..
		Vel. m. p. s. .	6·0	7·0	12·0	14·0	..	..	..
14th July, 1930 .	14 40	Direction .	260	285	295	270	270	..	..
		Vel. m. p. s. .	6·0	8·0	17·0	15·5	14·0	..	..
15th July, 1930 .	14 52	Direction .	260	280	275	275	..	..	..
		Vel. m. p. s. .	8·0	10·0	19·0	9·0	..	..	..
16th July, 1930 .	15 04	Direction .	270	290	295	295	..	..	..
		Vel. m. p. s. .	11·0	15·5	17·0	14·0	..	..	..
17th July, 1930 .	14 52	Direction .	270	280	295	..	..	..	..
		Vel. m. p. s. .	13·5	12·0	22·0	..	..	..	..

The trajectories of air at 2 km. reaching Akyab and Rangoon (*Fig. 33b*) make it strikingly evident that there was a strong horizontal velocity gradient off the Arakan Coast favourable for the formation of a cyclonic vortex. *Figures 33a* and *33b* also show that the region of rain and squalls in the Bay was where the accelerated air, south-westerly at the surface and westerly above, was flowing into an area previously filled with old monsoon air. It is instructive to note that there was not any large rainfall on the west coast of India on any day from the 9th to the 14th, and that although on the 14th the direction of the north-westerly air overrunning the Deccan changed to west or west-south-west, the trajectories do not suggest particularly low latitudes as origin for these currents.

15th July, 1930.

On the morning of this day, the area of squally weather had moved northward (*Fig. 34a*) and the monsoon air had begun to feed into the low over the head of the Bay. The

trajectories at 2 km. of this day's morning (*Fig. 34b*) and of the previous two days show that the monsoon air was still meeting old monsoon air which had been for many days in regions where instability showers were of daily occurrence. Air from Assam and Upper Burma was being drawn in as can be seen from the trajectories of air at 2 and 3 km. at Patna and Dacca. The monsoon air was definitely cooler at the surface. A remarkable change happened in the upper winds of North-West India between the morning and the afternoon of the 15th. The winds at 2, 3 and 4 kms. which were weak and southerly in Rajputana and the west United Provinces became westerly and increased in strength. The distribution of rainfall recorded on the 16th morning and shown in *Fig. 34b* shows heavy falls on the Arakan Coast. Though the rainfall was frontal in character, it was very much influenced by orography. This is also true of the rainfall distribution in Orissa and Bihar.

16th July, 1930.

With the forced north-westerly movement of the moist air of the monsoon parallel to the Arakan Hills the depression intensified into a storm and on the morning of the 16th its centre lay a few miles north of Cox's Bazaar. The worst weather in the Bay was experienced to the south of the front marked in *Fig. 35a*. Continuous heavy rainfall occurred in the neighbourhood of the storm centre and preceded it as the monsoon current moved north-westwards under the influence of the Chin and Lushai Hills. There was also fairly concentrated heavy rainfall to the east of the Chota Nagpur Hills attended with thunder. The scattered nature of this heavy rainfall and the fact that the 2 km. wind supply at Dacca and Calcutta on the morning of the 16th were from Upper Burma travelling comparatively slowly, *Fig. 35b*, show that the falls in south-west and Central Bengal were not due to fresh monsoon air being brought in, but rather due to old monsoon air at 2 km. and above moving southward over a moister layer of local origin. It will be noticed that upper air from NW India had not begun to take part in the depression. Further west in the United Provinces and the Central Provinces, air at lower levels from the North Arabian Sea was meeting old air and causing moderately heavy precipitation attended with thunderstorms.

At 8 hours on the 16th, surface temperatures in the monsoon sector in the Bay and in Burma Coast were of the order of 78—80° F., in south Bengal 82° F. and in north Bengal 88° F.

17th July, 1930.

So far, the rainfall in Bengal was due to the overrunning of the normally moist surface layers of south Bengal by the north-easterly old monsoon air from north Burma and Assam. With the advent of a fresh air stream from the Bay of Bengal parallel to the Chin and Lushai Hills, the old monsoon air had an opportunity of meeting fresh monsoon air further to the north-east and the trajectories and rainfall drawn in *Fig. 36b* show how the heavy rainfall occurred within the monsoon air sector where the upper old monsoon air had the first opportunity of climbing it. This is a feature repeatedly made evident by these charts.

The persistent occurrence of heavy rainfall in the plains of SW Bengal to the east of the Orissa Hills is a consequence of orography which is well worthy of note.

18th July, 1930.

Both on the 17th and the 18th, three more or less distinct sectors can be recognised, (1) Monsoon Air Sector, (2) Assam Air Sector and (3) North-Westerly Air Sector. Of these (2) and (3) had little contrast (*cf.* upper winds at Allahabad and Patna) and on the 18th, with the curving round under the influence of the hills, (1) was losing its individuality. The influence exercised by the Khasi Hills in deflecting the moist cold monsoon stream is shown by the shape and position of the area of heavy rainfall during the next 24 hours (*Fig. 37b*). The old continental air from the Punjab and the air from Assam were tending to surround the monsoon air.

19th July, 1930.

No fresh monsoon air was being drawn into Bengal (*Figs. 38a* and *38b*). The area over which rain was falling at 8 hours in the morning of the 19th was practically where heavy falls had occurred during the previous 24 hours and the surface air was cooler than in the surrounding area. The upper air trajectories at Chittagong and Calcutta show that the air supply at 2 km. was old continental air with little difference in properties from the old monsoon air. At 0·5 and 1 km. it was either from north Bay or from the west. The weak front between the north-east and north-west Indian air streams was running from near the centre of the depression in a north-westerly direction to between Delhi and Agra.

To the south of Lat. 23° N., fresh westerly air from Arabian Sea was advancing eastward as shown by the 2 km. trajectory at Jubbulpore on the 18th morning and at Sambalpur on the 19th.

Heavy rainfall occurred during the next 24 hours at the following two areas : (1) At the Chota Nagpur Hills where moist air was first projected against the hill on the southern side in the lower layers followed by old monsoon air from the north-east. The orography, the backing of the hills by moist westerly air not less than 2 km. in thickness, and the incidence of upper north-easterly current over an intervening area of shallow north-westerly current were all contributory to this heavy rainfall.[1] (2) At the Vindhya Hills, where the westerly monsoon current advancing along the Narbadha valley and up to the Vindhyas was met by the north-westerly continental air current.

It is interesting to note that these two areas of heavy rainfall show themselves distinctly separate and that in the first case, the rainfall area is continued most markedly in a north-easterly direction while in the latter, it progresses in a north-westerly direction.

20th July, 1930.

The upper air observations on this day show that the surface of separation between the easterly and north-westerly air currents on the northern side of the depression was sloping upward towards the south-west (*Figs. 39a* and *39b*). As on the previous day, the heavy rainfall area during the subsequent 24 hours could be approximately divided into two—one in which the north-easterly and the other in which the north-westerly upper current was operative. As usual, these currents became effective in causing heavy rainfall only where the monsoon current exceeded a certain limiting thickness. On the 20th morning alto-stratus clouds (10) at Hoshangabad and alto-cumulus clouds (4) at Khandwa (both in the monsoon sector) were coming from the west. It will be useful here to summarise the weather at a few stations near which the centre of the depression passed.

E

TABLE 8.

(The symbols for weather remarks are the same as in the India Weather Message Code, 1931.)

Date. 1930.	Time. Hrs.	Pressure. Ins.	Temperature °F. D. B.	Temperature °F. W. B.	Wind.	Low or middle cloud with direction.	Rain in previous 24 hours.	Weather Remarks.
Jubbulpore (Lat. 23° 10′ N., Long. 79° 59′ E.)								
19th July .	8	29·55	76·8	75·2	..	SK 10 NW	0·95″	r 5 to 8 hrs. Shower 15 hrs.
	17	·40	..	..	..	AK 8 NE	..	d 20 hrs. to 4 hrs. on 20th July.
20th July .	8	·44	75·4	75·0	NW 1	N 10 NW	2·21″	rr 10 to 16 hrs., r with T, L and strong wind at night.
	17	·29	74·2	74·0	WNW 3	N 10 SW	..	
21st July .	8	·37	75·4	73·8	SSE 2	SK 10 S	9·95″	d 5 to 7 hrs. and 10 hrs.
	17	·36	79·2	74·2	WSW 1	AK 8 SW	..	
Saugor (Lat. 23° 50′ N., Long. 78° 50′ E.)								
20th July .	8	·50	72·4	71·9	WNW 1	N 10 NW	1·82″	r T 1 to 7 hrs. rr° 7-30 to 20 hrs.
	17	·34	75·9	75·1	WNW 3	N 10 W	..	rr 20 to 3 hrs. on 21st.
21st July .	8	·31	73·9	73·3	ENE 2	N 10 NE	4·42″	d° 3 to 10 hrs., 15 to 19 and 23 to 3 hrs. on 22nd.
	17	·32	75·0	73·1	SW 3	N 8 SW	..	
22nd July .	8	·47	72·6	71·1	SSW 1	N 10 SW	0·05″	d° 7 to 8-30 hrs.
Neemuch (Lat. 24° 27′ N., Long. 74° 52′ E.)								
20th July .	8	·57	83·5	78·5	W 2	N 1 ? SK 3	0·13″	
	17	·43	78·0	76·0	W 3	N 2 ?	..	r 20-15 to 20-45 hrs. and 21 to 4-30 hrs. on 21st.
21st July .	8	·46	80·0	77·0	NW 2	N 2 ?	2·27″	r 10-30 to 10-45 hrs., T 19-10 to 19-15 hrs., r 18-10 to 21-05 hrs. Surface wind changed from E to W at about 18 hrs.
	17	·33	78·0	76·5	NE 4	N 2 SW	..	
22nd July .	8	·39	74·5	73·0	SW 3	N 1 SW SK 3 ?	2·72″	
	17	·35	78·0	75·0	SW 3	N 1 SW SK 1 ?	..	Light shower at 19 hrs.
Mount Abu (Lat. 24° 36′ N., Long. 72° 43′ E.)*								
21st July .	8	26·34	66·7	66·7	WSW 3	N ?	0·00″	Fog whole day, d at 15 hrs., rr from 22-30 hrs.
	17	·24	69·7	66·7	W 2	N W	..	
22nd July .	8	·24	69·7	69·7	NE 2	N NE	3·90″	rr till 6 hrs., r° 12 to 15 hrs., T at 17 hrs.
	17	·17	71·3	69·7	N 2	KN N	..	
23rd July .	8	·26	68·7	67·9	SE 2	..	0·76″	

* Pressures at Mount Abu are reduced to 1 km. above sea level.

TABLE 8—*contd.*

Date. 1930.	Time. Hrs.	Pressure. Ins.	Temperature °F. D. B.	Temperature °F. W. B.	Wind.	Low or middle cloud with direction.	Rain in previous 24 hours.	Weather Remarks.
Ahmedabad (Lat. 23° 02′ N., Long. 72° 38′ E.)								
21st July .	8	29·55	81·6	77·1	WSW 2	AS	0·11″	Shower at 16 hrs., rr from 17-30 hrs.
	17	·44	83·3	79·7	Calm	N SW	..	
22nd July .	8	·46	75·6	75·2	SW 3	N	2·65″	rr till 11 hrs., dd from 16-55 hrs.
	17	·39	78·5	77·5	WSW 2	N	..	
23rd July .	8	·46	76·5	75·8	SSW 2	N SW	0·32″	dd throughout day. Overcast.
	17	·46	77·7	76·7	SW 3	FrN SW	..	
Rajkot (Lat. 22° 18′ N., Long. 70° 56′ E.)								
21st July .	8	29·56	82·0	76·5	WSW 6	K 5 SW	0·00″	d° from 22 hrs.
	17	·45	87·0	75·5	WSW 6	N 10 SW	..	
22nd July .	8	·47	76·0	75·0	WSW 4	N 10 SW	3·76″	rr 3 to 9 hrs., r 9 to 17 hrs. and rr 17 to 24 hrs.
	17	·40	75·5	74·5	SSW 4	N 10 SW	..	
23rd July .	8	·46	75·5	74·5	SW 5	S 10 SW	11·36″	rr 0 to 4 hrs., d 4 to 9 hrs., d occasionally 9 to 17 hrs., d° 17 to 20 hrs.
	17	·42	81·5	77·5	SSW 5	N 10 SW	..	
Hyderabad (Sind) (Lat. 25° 23′ N., Long. 68° 24′ E.)								
22nd July .	8	29·41	84·8	81·0	Calm	N 7	0·14″	T, L previous night, 21-30 to 22-30 hrs.
	17	·32	82·2	77·8	NNW 6	KN 6	..	≡S≡ 16-40 to 17-00 hrs. rain.
23rd July .	8	·37	84·2	80·0	N 3	N	0·44″	Showers 15 to 15-40 hrs., d 21 to 24 hrs.
	17	·35	83·4	81·6	NW 1	KN	..	
24th July .	8	·53	81·6	79·4	SE 1	N	0·32″	d 0 to 5 hrs.

N.B.—Rainfall is not entered against 17 hrs. in the above Table, as rainfall was measured only once a day at 8 hrs.

At Saugor, on the morning of the 20th the temperatures of both wet and dry bulbs were comparatively low, as some showery rain accompanied by thunder had already occurred. The continuous rainfall during the day time of the 20th should be considered as warm-front rain due to the ascent of north-easterly air over the rain-cooled north-westerly. The heavy continuous rainfall on the night of the same date occurred after the westerly thicker monsoon current had arrived. On the morning of the 21st the nimbus direction was from NE and it changed later to SW. The weather at Jubbulpore on the night of the 20th, with heavy rain, strong wind and thunderstorm, and the changes of low cloud direction on the 20th and 21st suggest that the advance of the southerly or south-westerly air immediately on the eastern side of the low was in the nature of a cold front.

The behaviour of upper winds and the nature of weather experienced at Agra between the 19th and 22nd are interesting as showing the relative qualities of the north-westerly, easterly, and south-easterly air currents. Some pilot balloon trajectories on these dates

are reproduced in *Fig. 43*. As will be seen from the trajectory at 6 hours on the 20th the easterly old monsoon current had come up that time at levels above 1·3 km. over Agra. There was a thunderstorm at Agra at about 15 hours on the 20th attended by a rapid fall of both dry and wet bulb temperatures (*Fig. 44*). Momentarily, the surface wind changed from N to SE and later became NW. The easterly air first came in as a moist current above 1 km ; and the instability was due to the large lapse-rate near the ground and the supply of moisture above 1 km. Once instability rain has cooled the northerly air mass and thus removed the effect of surface heating, it behaves as cold air with respect to the old monsoon air. The large fall of temperature of both dry and wet bulbs after the rainfall was obviously due to the comparative dryness of the pre-existing air. The easterly old monsoon air (*see* trajectory of 21st at 6 hours) was replaced by comparatively fresher and cooler south-easterly monsoon air by the morning of the 22nd. The fall of temperature at 23 hours on the night of the 21st may be noted.

21st July, 1930.

The warm-front between the easterly and north-westerly streams was well-developed on this day (*Figs. 40a* and *40b*). The upper wind directions at Ajmer, Lat. 26° 27′ N., Long. 74° 44′ E., on the 20th and 21st are given below :—

TABLE 9.

Date.	Time.		Height in km.							
			0·6	1·0	1·5	2·0	2·5	3·0	3·5	4·0
20th July .	16 05	Direction .	275	270	310	320	340	340	25	30
		Vel. m. p. s.	6·5	8·0	7·0	7·5	4·0	4·5	4·0	4·0
21st July .	06 16	Direction .	290	310	360	80	55	..	..	..
		Vel. m. p. s.	8·0	8·0	6·0	5·0	4·5	..	..	..

At Kotah (Lat. 25° 10′ N., Long. 75° 52′ E.) on the morning of the 21st, both strato-cumulus and alto-stratus clouds were coming from the north-east.

From the weather records at Ahmedabad and Rajkot given in *Table 9*, it will be seen that the rainfall at both those places was of the continuous warm-front type such as occurred at Saugor on the night of the 20th. Both dry and wet bulb temperatures at Mount Abu on the morning of the 22nd were higher than those on the previous days though a rainfall of 3·9″ had occurred during the preceding 24 hours. The rainfalls in Sind and Rajputana, however, were of the thunderstorm type. These suggest that, in Kathiawar, north-westerly dry upper air was not coming into conflict with monsoon air, the shallow west-north-westerly winds at Karachi and Ajmer notwithstanding. On this day, another feeble depression was developing in the north-west corner of the Bay with a feeble warm-front along a line running to the north-west from Balasore. The fact that rain was falling at places where the wind was westerly or south-westerly shows that the easterly current was ascending. It is important to notice that there was no north-westerly fresh continental air involved in the formation of this new depression.

22nd July, 1930.

The chart (*Fig. 41a*) shows that the Aravallis had the effect of concentrating the warm-front rain on itself and preventing it from extending westwards. North-easterly warm

air had already arrived at Mount Abu and at upper levels it must have progressed further to the south-west. *Fig. 41b* shows that the heavy rainfall in Kathiawar occurred at the surface of convergence of this air with the fresh monsoon current. The heavy falls in Sind along the Indus were due partly to the orographic effect of the hills west of the river. The pre-existing presence of moisture at the lower levels of the Indus delta causing a cool surface layer which is usually about 1·5 km. thick at Karachi in this season was also a contributory cause. It will be noticed that the rainfall in Sind and Rajputana was mostly of thunderstorm type and this is what is to be expected considering that the previous air supply over the region was from Baluchistan and that it was into this that a moist supply of air was injected at levels of 1 and 2 km.

23rd July, 1930.

On the previous day, the depression was partly on the eastern side of the Aravallis and partly on the western side. This morning, it had entirely crossed over to the west with a front running in an east-south-easterly direction from Karachi (*Figs. 42a* and *42b*). The easterly deflected monsoon air had arrived at Quetta and, as showing the contrast between the old continental air and the easterly old monsoon air, the aeroplane temperatures and humidities obtained on this day and the previous and succeeding days at Quetta are given in *Fig. 45*. The comparative coolness and moistness of the monsoon air are evident.

It is not necessary to pursue the progress of the depressions further except to say that it was dissipated on the Baluchistan and Mekran Hills on the 24th.

In *Fig. 46* are shown in one consolidated diagram the positions of the centres of low pressure at 8 hours on each day from the 17th to the 23rd and the areas of heavy rainfall in every successive 24 hours. It shows the unsymmetrical nature of the distribution of heavy rainfall about the low pressure centre and the remarkable manner in which it is concentrated in the fresh monsoon sector in front of the lines where old monsoon or continental air attacks it.

The study of upper air conditions and of individual depressions during the monsoon leads to the following general conclusions.

(1) The formation of monsoon depressions in July and August is generally preceded by an acceleration of the monsoon air in the Deccan especially at 2 and 3 km.

(2) The Burmese mountains help to deflect this current northward and roll it up into a vortex.

(3) The air masses that initially meet are the accelerated monsoon air and old monsoon air.

(4) When near the Burma Coast, the old monsoon air is often mixed with air from Upper Burma and Siam, especially at levels above 2 km. The latter may be expected to be similar in properties to old monsoon air coming as it does from the region of rainfall of the Chinese monsoon.

(5) Squally weather and heavy rainfall occur within the monsoon sector adjacent to the place where either the old monsoon air from NE India or continental air from NW India meets monsoon air of more than 2 km. thickness ; in addition to frontal action adiabatic expansion due to large hori-

zontal gradients of pressure is an important cause of producing rainfall within the humid monsoon air mass travelling partially across the isobars towards the centre of low pressure.

(6) The main front is formed between fresh monsoon air and old monsoon air in which the former behaves as a cold air mass and the latter as a warm air mass. Fronts also form between the fresh or old monsoon air and surface heated continental air. In this case the continental air is generally warmer up to about 3 km. and colder above.

(7) Depressions retain their strength so long as there is a good supply of fresh monsoon and old monsoon air.

(8) When depressions move into Rajputana owing to the gradual replacement of old monsoon air by surface heated continental air the monsoon air rapidly gets desiccated and the depression dies down.

(9) The entry of monsoon air into Rajputana, Sind and the-N.-W. Frontier Province causes fall of temperature and increase of humidity between 1 and 3 km. and is invariably accompanied by thunderstorms.

Some general remarks regarding the properties of continental and maritime air masses involved in the storms of the Indian Seas.

A comparison of the places of origin of storms in the Indian seas and the stream lines of upper winds at 2 and 3 km. shows that storms generally originate or strengthen at places where there is the best chance for air from land to meet sufficiently deep maritime air at an angle. The atmospheric effects that will ensue as a result of the coming together of these air masses will obviously depend on their properties as regards temperature and humidity and on the circumstances of their movement. The properties of land air over India, especially over North India, change considerably during the course of the year. During winter the continental air that drains into the Bay of Bengal is cooler and drier than the maritime air that enters the south of the Bay from the east and in the storms that form in this season, the continental air behaves as cold air mass and the maritime air as warm air mass at all levels from the surface up to at least 6 or 8 km.[9] Conditions are partially altered in the pre-monsoon months, April, May and part of June. Owing to the differential heating of land and sea, the air over land has in its lower layers a higher temperature than that over sea, but as this is accompanied by a larger lapse-rate near the ground, the temperature conditions get reversed at higher levels. In the storms of this season, therefore, the continental air behaves as " warm air " at the surface and as " cold air " at higher levels, generally above 2 or 3 km. There is a still further change in the air over the major portion of North India during the monsoon months July and August. Except in North-West India, the air over North India is generally old monsoon air—that is air which for the most part originally came into the country as fresh monsoon air but whose temperature and moisture content in its higher layers have been increased owing to precipitation and insolation. Although at the surface the relative humidity of this air is smaller than that of fresh monsoon air, in consequence of its higher

[9] K. R. Ramanathan and A. A. Narayana Iyer: Ind. Met. Dept., Sc. Notes, Vol. III, No. 18, 1930; and S. Mal and B. N. Desai: Ind. Met. Dept., Sc. Notes, Vol. IV, No. 39, 1931.

temperature the absolute humidity is higher. If therefore extensive cloud formation can occur in this air mass below the level at which its temperature would otherwise become equal to that of the fresh monsoon air, the old monsoon air would acquire above the condensation level a lapse-rate approaching that of saturation adiabatic and behave as a warm air mass with respect to fresh monsoon air. Indeed, it is known from the results of sounding balloon ascents at Agra that, during July and August, the height-temperature curve there follows closely the curve of saturation adiabatic and that even between 2 and 4 kms. the lapse-rate is only 4·5°C. km.[10] This picture, however, of old monsoon air ascending over fresh monsoon air at a warm-front in the depressions of the monsoon season is too simple. There is often intercalated between the fresh and old monsoon airs a comparatively drier air stream of surface-heated continental air from NW India. The continental air behaves at levels of 2—4 km.*

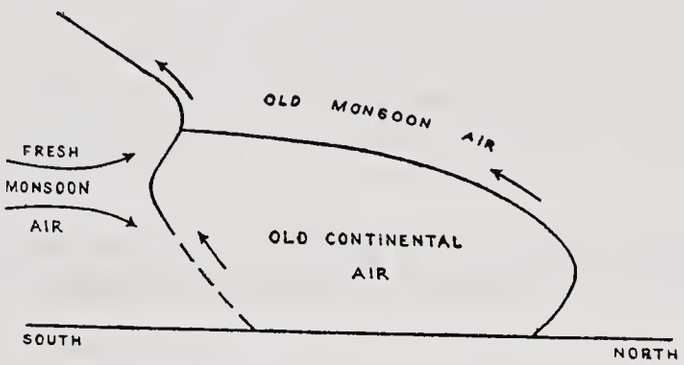


FIG. 47. SCHEMATIC DIAGRAM SHOWING STRUCTURE OF MONSOON DEPRESSION WHEN OVER CENTRAL INDIA.

as cold air with respect to old monsoon air, and if rain has already fallen within it, at lower levels also. We have no definite information as to the level to which high humidity extends in the fresh monsoon stream or the level at which the continental air would begin to behave as cold air mass towards fresh monsoon air, but it may be expected to be higher than in the case of old monsoon air. A vertical section of the composite front such as often forms over Central India in connection with monsoon depressions is shown in *Fig. 47*. It is obvious that more extended upper air observations of both temperature and humidity are much needed for the elucidation of many important points.

We wish to acknowledge our thanks to Mr. A. Narayanan for his help in the preparation of normal wind data for the stream-line diagrams and to Messrs. S. S. Kohli and L. V. Joshi for help in the preparation of detailed rainfall maps.

Our thanks are also due to Mr. S. Basu and Dr. S. C. Roy for their helpful criticisms.

[10] K. R. Ramanathan, "Sounding Balloon Ascents at Agra", Mem. Ind. Met. Dep., Vol. 25, Part 5, 1930.

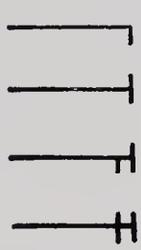
* As already remarked, this height is liable to variation depending on the recent history of the continental air mass.

Explanation of symbols used in the charts of weather at 8 hrs. and of history of upper air movements.

(a) *Weather charts.*

Wind velocity.

The number of feathers in the wind arrows represents the Beaufort number of the wind, *e.g.*,



Beaufort No. 1

,, ,, 2

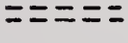
,, ,, 3

,, ,, 4

Winds at 0·5 Km. at pilot balloon stations, at surface at hill stations of nearly 0·5 Km. height, and at sea are represented by full arrows; those at surface at plain stations by broken arrows.

Fronts.

Well marked front.

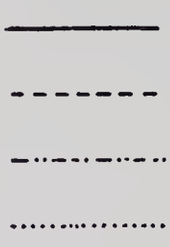


Diffuse front.

Region where rain was falling at the time of observations.

(b) *Upper air movement charts.*

Trajectories of air movement at



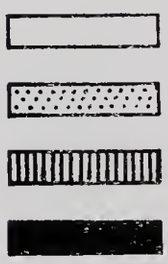
1 Km.

2 Km.

3 Km.

4 Km.

Amount of rain in next 24 hrs.



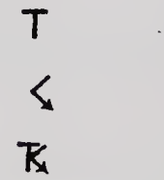
$<0{\cdot}5''$

$0{\cdot}5''$-$2{\cdot}0''$

$2{\cdot}0''$-$4{\cdot}0''$

$>4{\cdot}0''$

Remarks about weather during next 24 hrs.



T Thunder

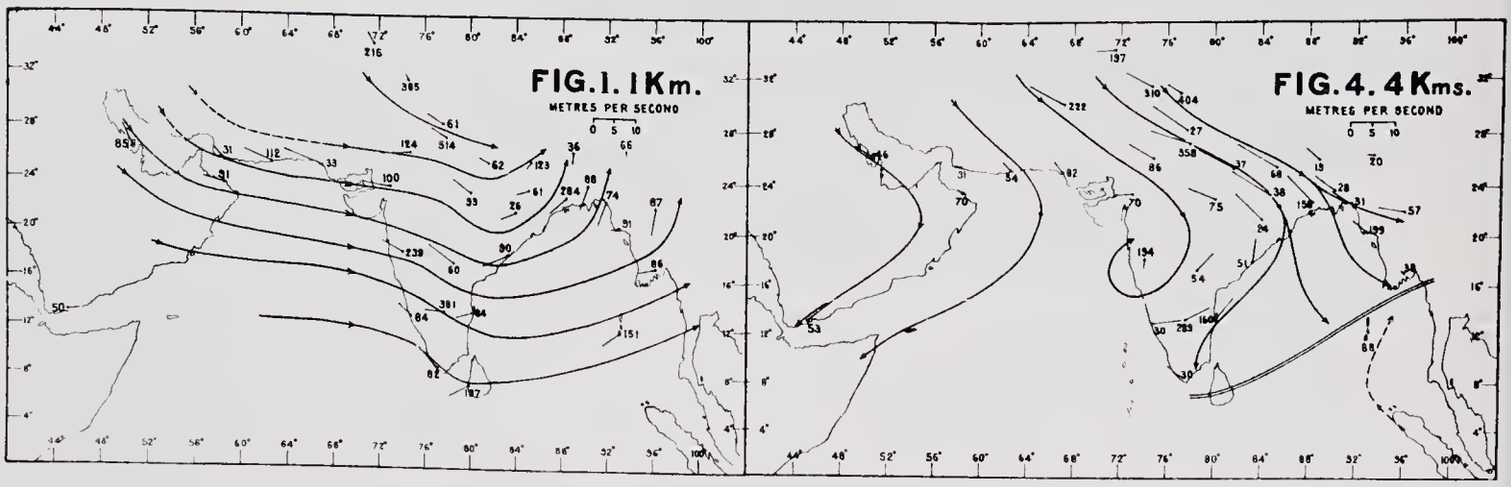
Lightning.

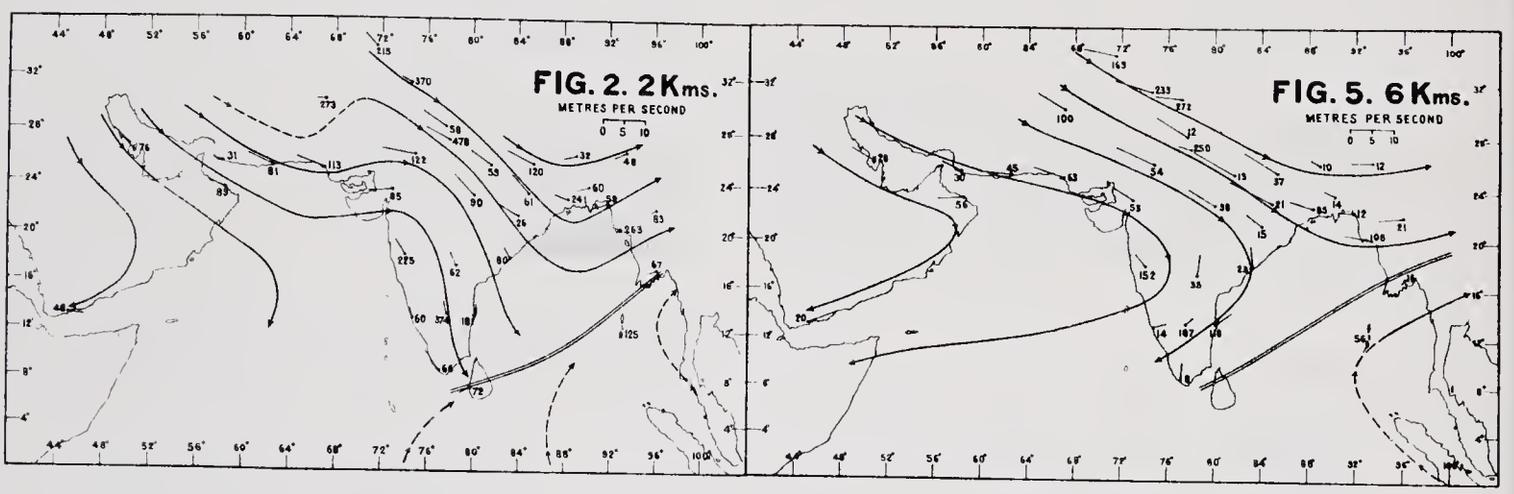
Thunderstorm.

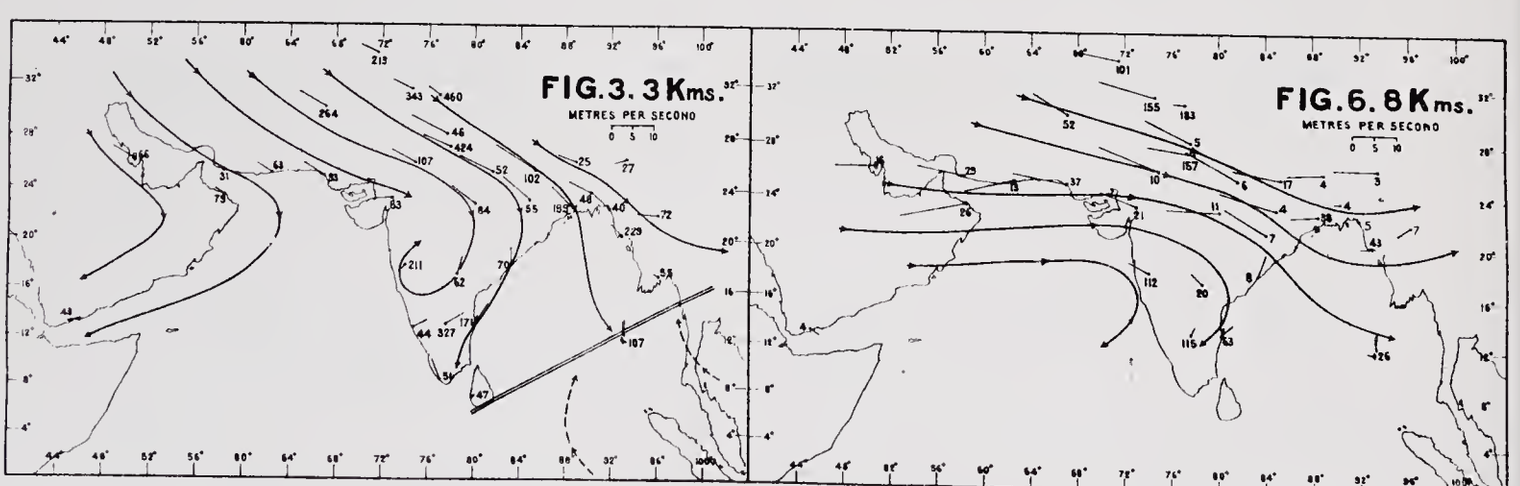
N.B.—Positions of fronts at 2 Km. are marked on these charts on a few days.

MGIPC—M 4-9-33—350.

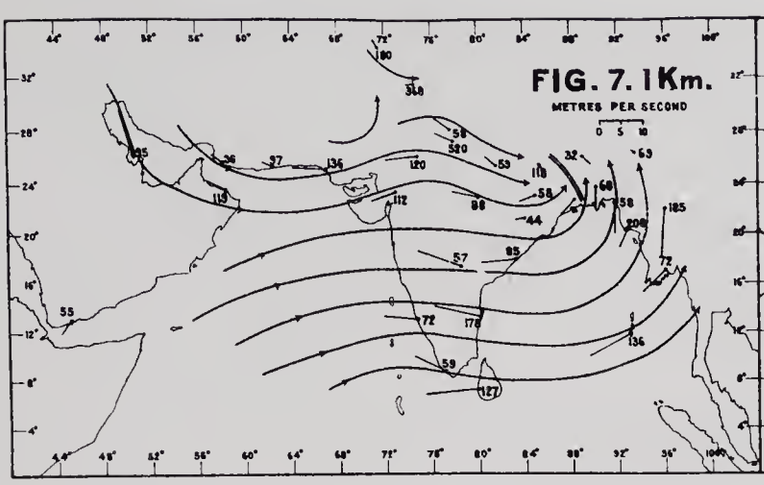
NORMAL WINDS AND STREAM LINES OVER INDIA IN MAY

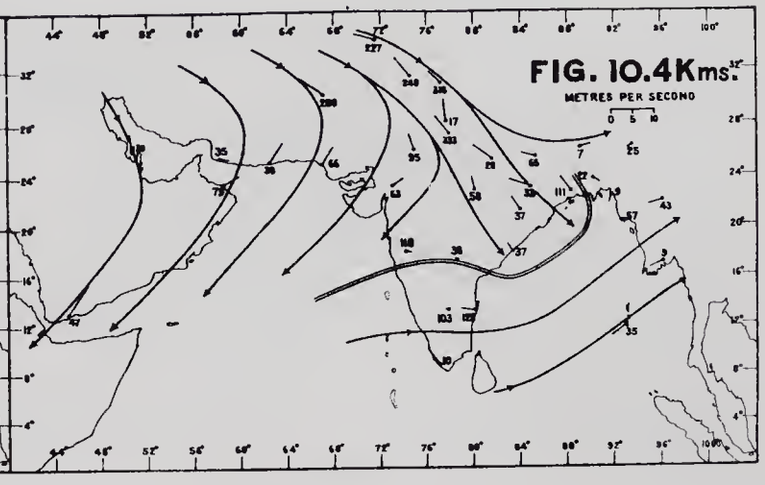


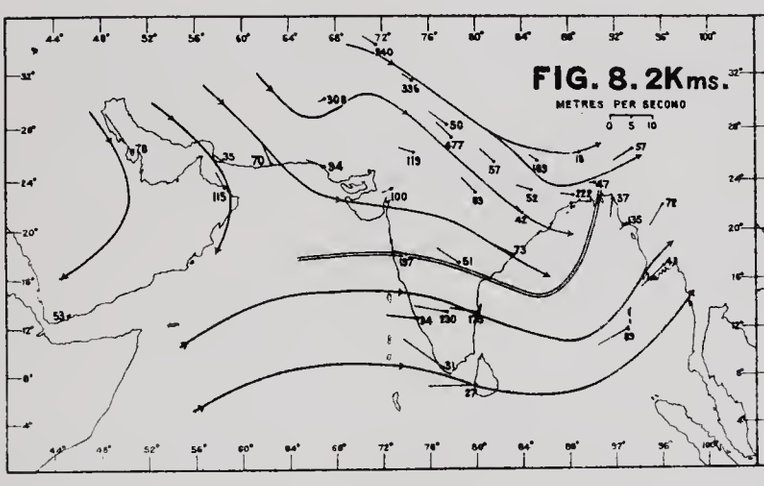


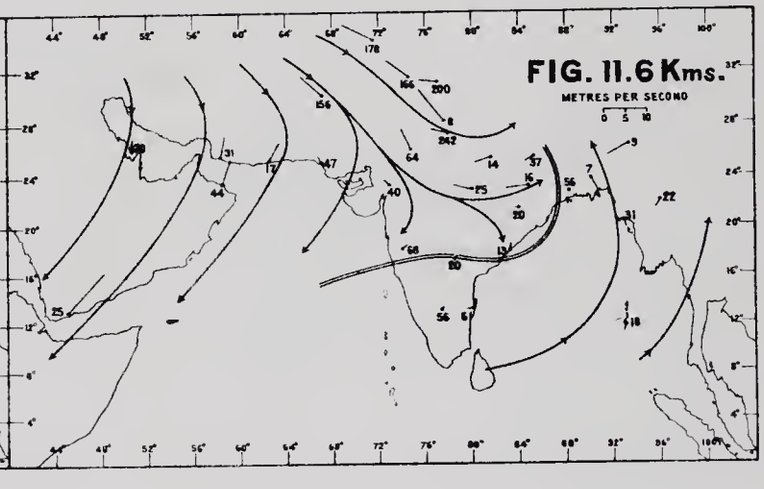


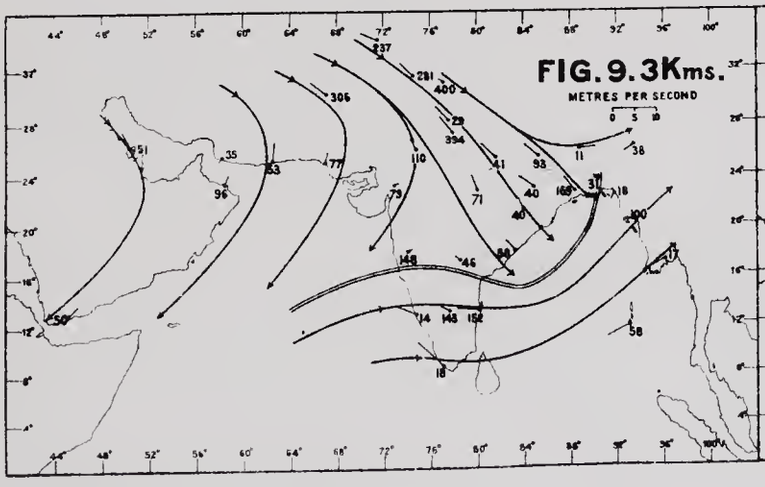
NORMAL WINDS AND STREAM LINES OVER INDIA IN JUNE

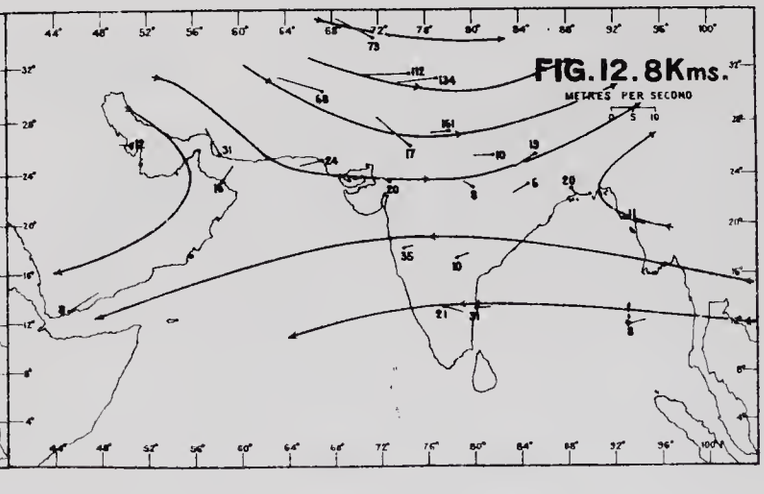




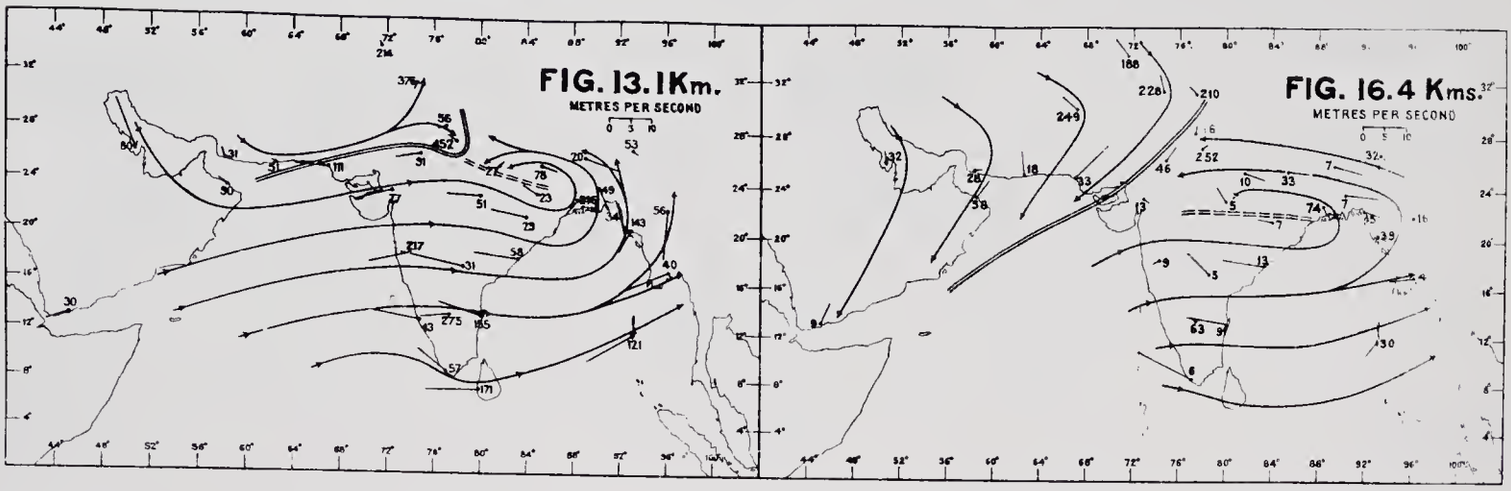


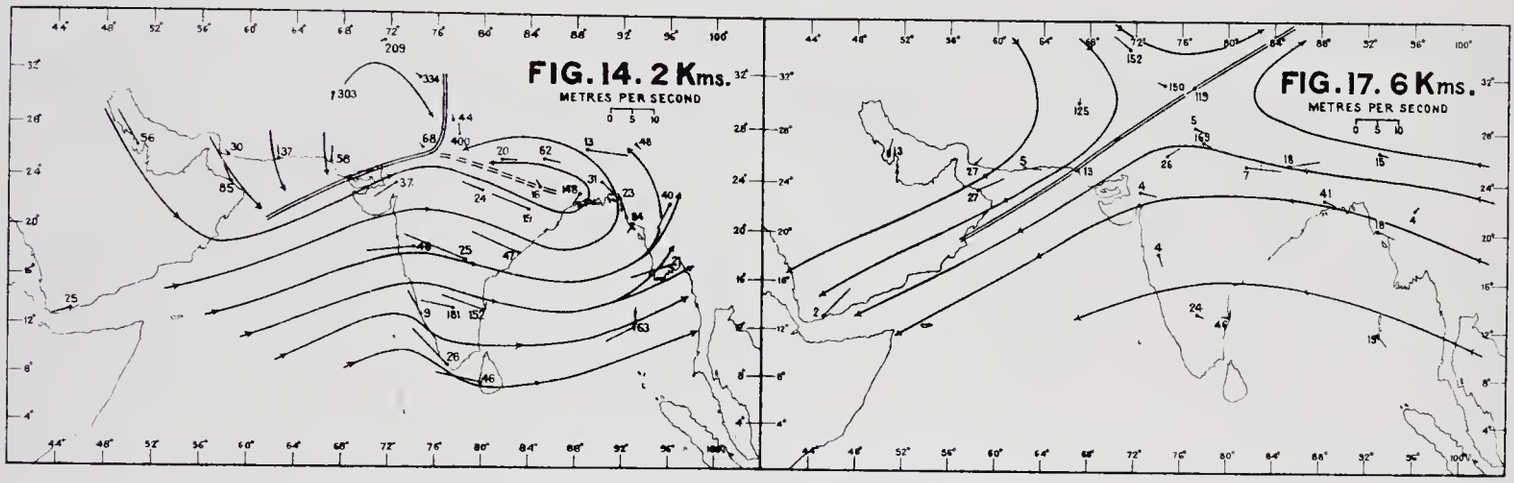


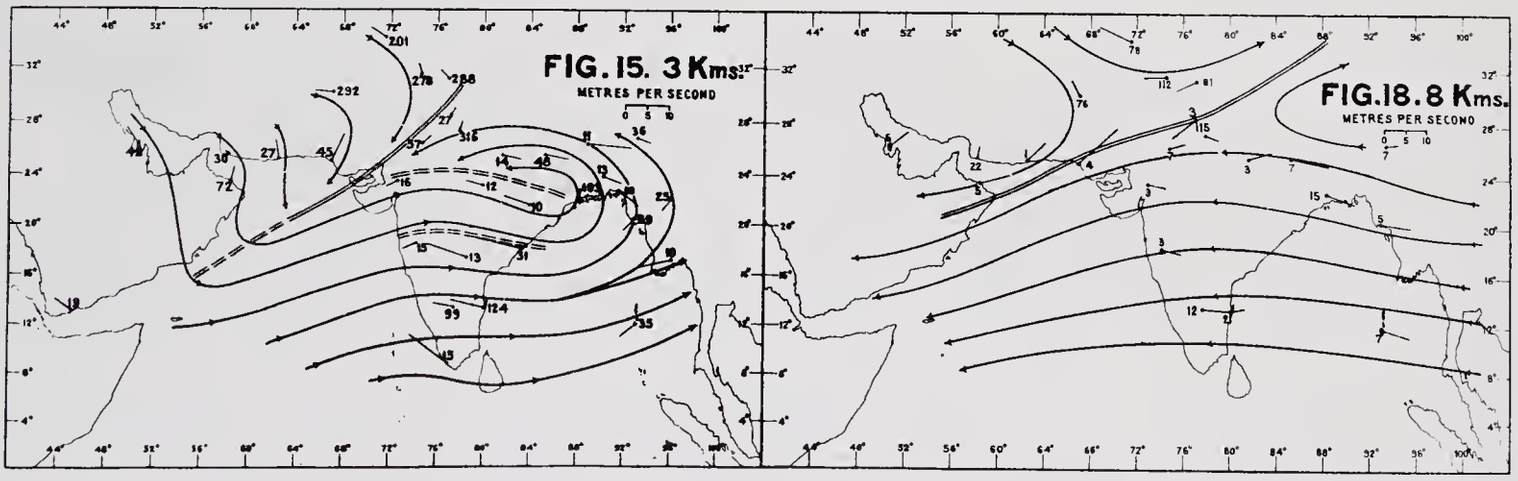




NORMAL WINDS AND STREAM LINES OVER INDIA IN JULY







G.P.Z.O. Poona, 1933.

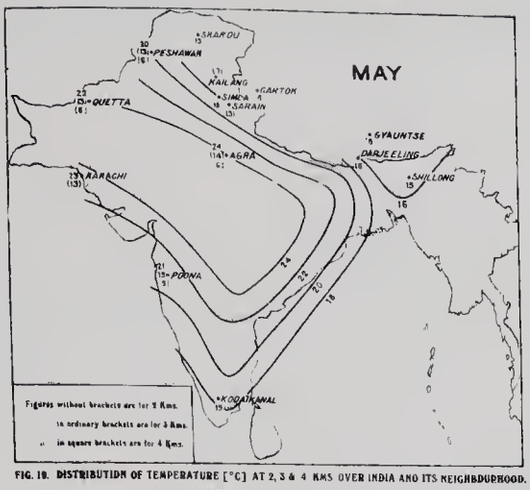


FIG. 19. DISTRIBUTION OF TEMPERATURE [°C] AT 2, 3 & 4 KMS OVER INDIA AND ITS NEIGHBOURHOOD.
(ISOTHERMS REFER TO 2 KMS.)

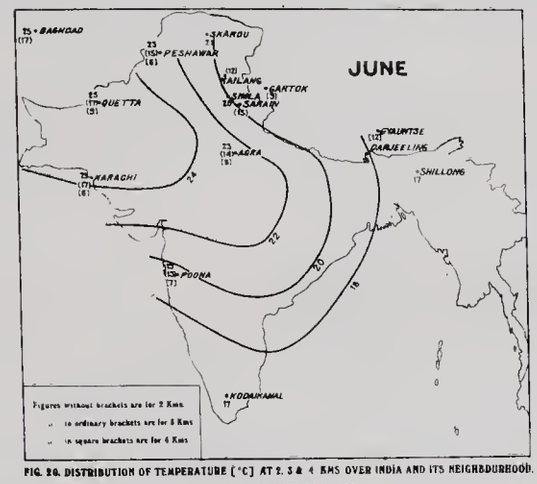


FIG. 20. DISTRIBUTION OF TEMPERATURE [°C] AT 2, 3 & 4 KMS OVER INDIA AND ITS NEIGHBOURHOOD.
(ISOTHERMS REFER TO 2 KMS.)

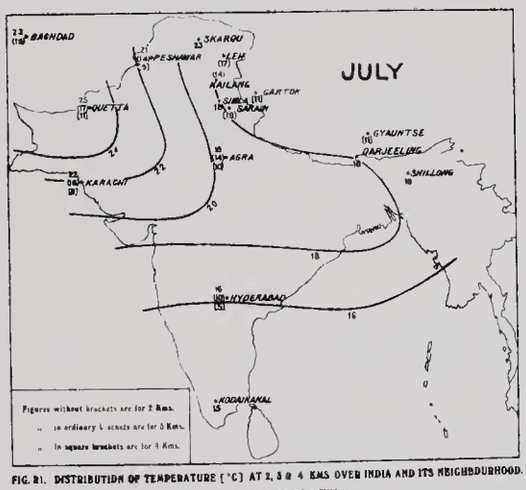
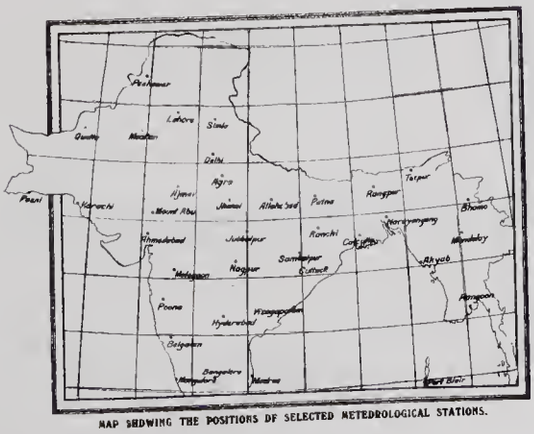


FIG. 21. DISTRIBUTION OF TEMPERATURE [°C] AT 2, 3 & 4 KMS OVER INDIA AND ITS NEIGHBOURHOOD.
(ISOTHERMS REFER TO 2 KMS.)



MAP SHEWING THE POSITIONS OF SELECTED METEOROLOGICAL STATIONS.

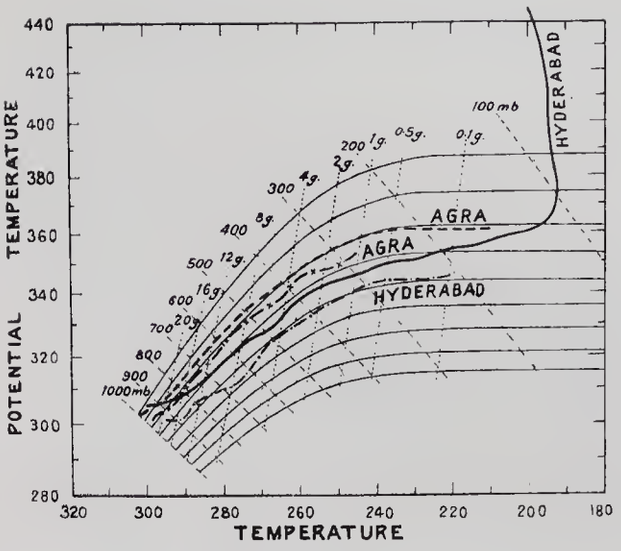
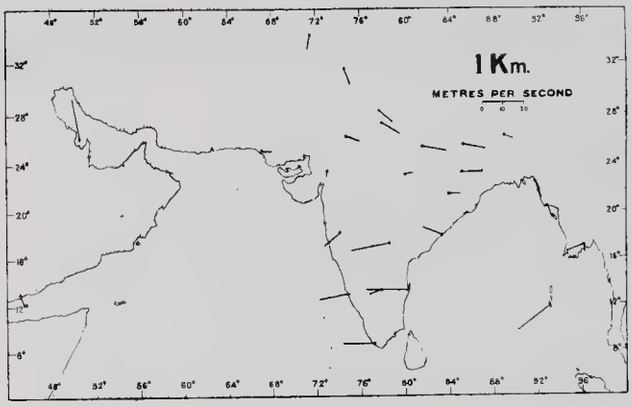
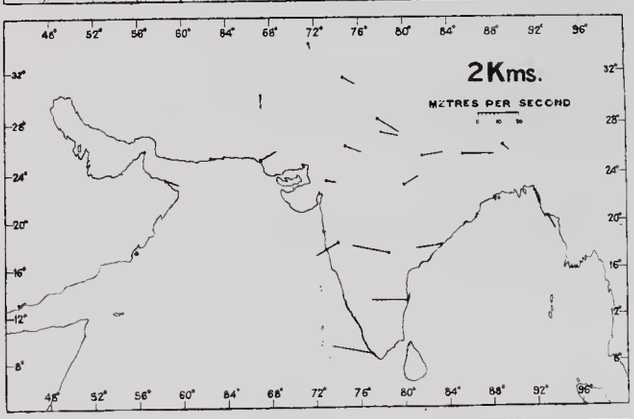


FIG. 22. TEPHIGRAMS AND DEW-POINT TEMPERATURE DIAGRAMS REPRESENTING
MEAN CONDITIONS OVER AGRA AND HYDERABAD (DECCAN) IN JULY.





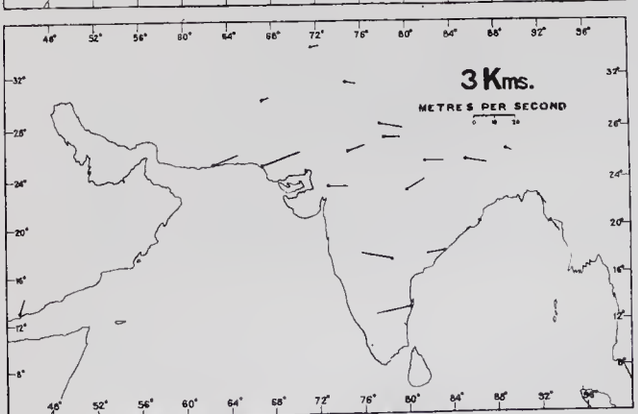


FIG. 23. UPPER WINDS AT 1, 2 AND 3 KMS. ON THE MORNING OF 27-6-1930.

G. P. Z. O. POONA, 1933.

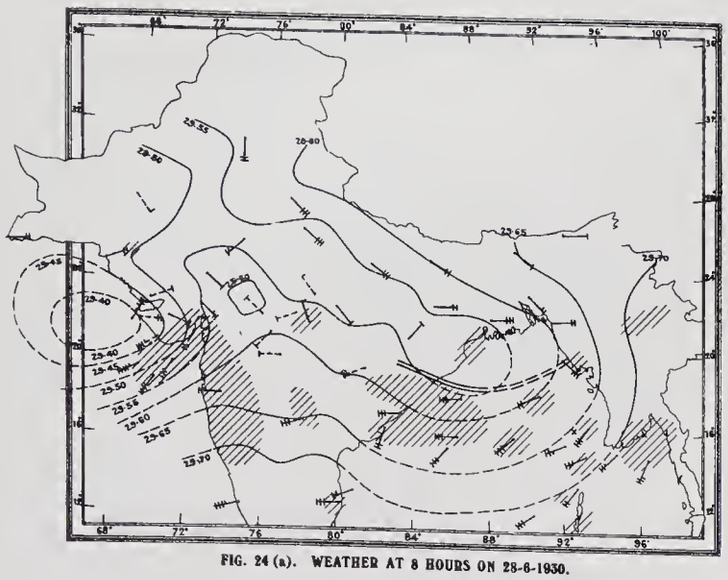


FIG. 24 (a). WEATHER AT 8 HOURS ON 28-6-1930.

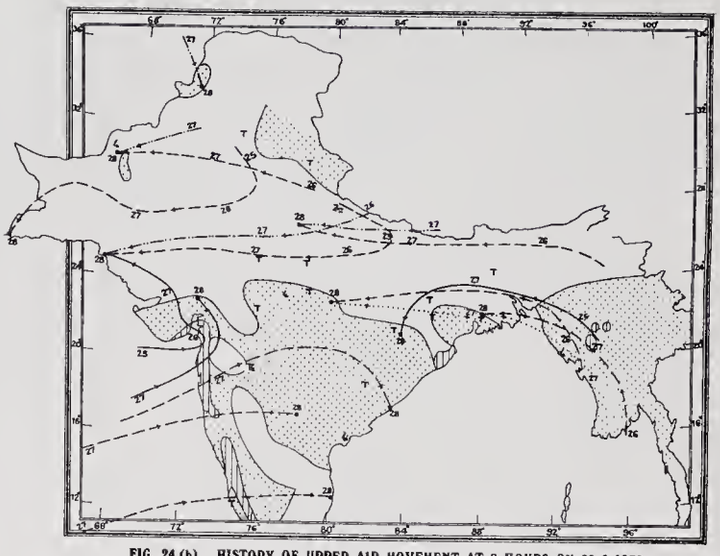


FIG. 24 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 28-6-1930 AND RAINFALL DURING NEXT 24 HOURS.

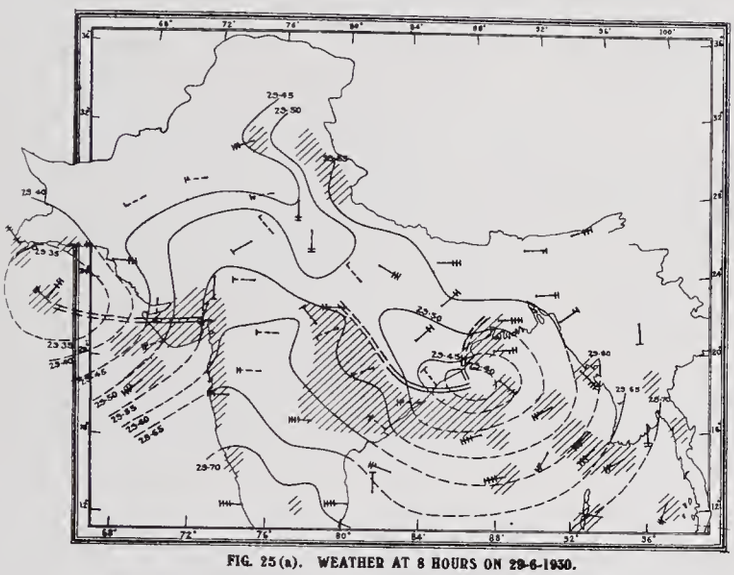


FIG. 25 (a). WEATHER AT 8 HOURS ON 29-6-1930.

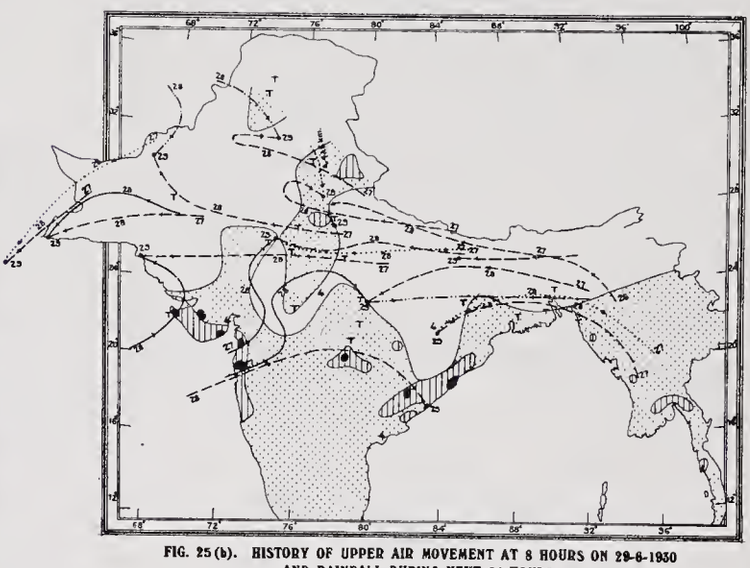


FIG. 25 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 29-6-1930 AND RAINFALL DURING NEXT 24 HOURS.

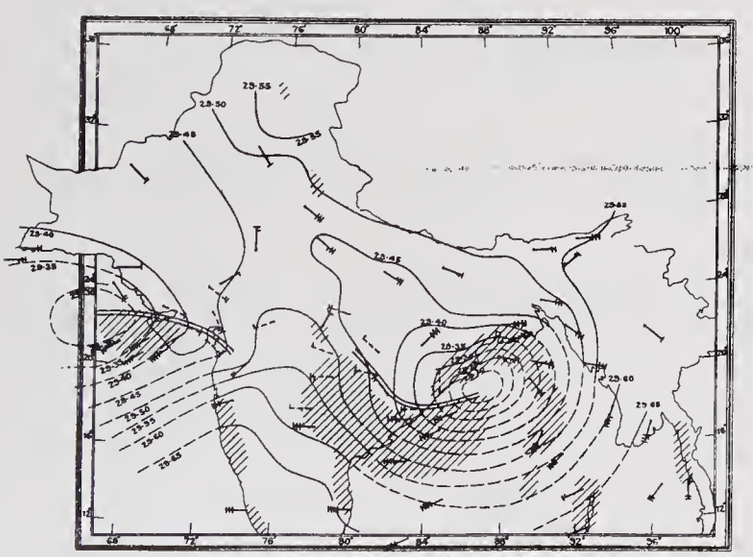


FIG. 26 (a). WEATHER AT 8 HOURS ON 30-6-1930.

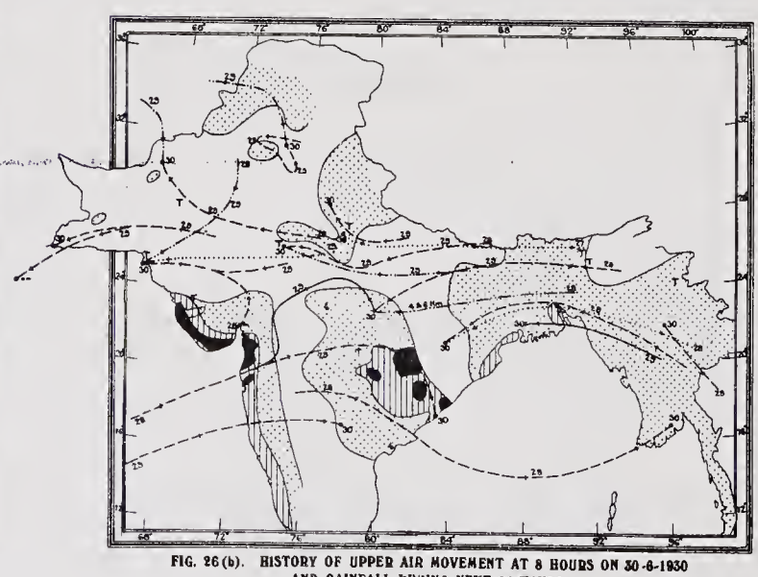


FIG. 26 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 30-6-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.I.O. POONA, 1933.

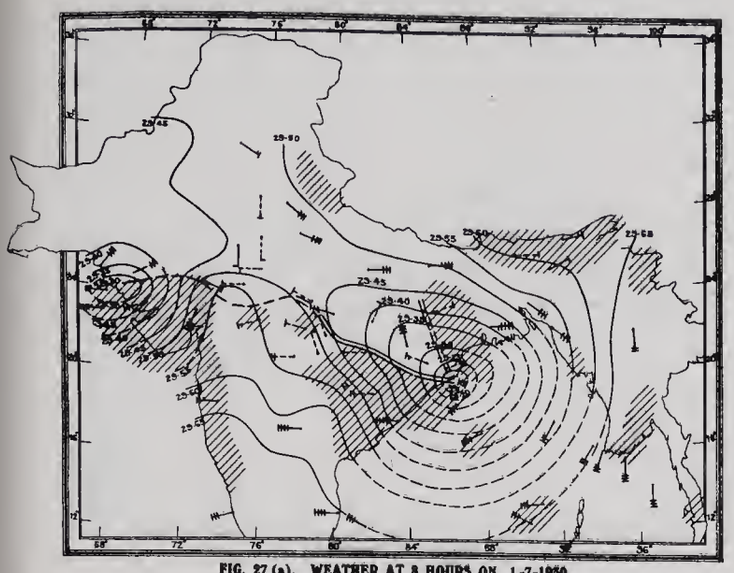


FIG. 27 (a). WEATHER AT 8 HOURS ON 1-7-1930.

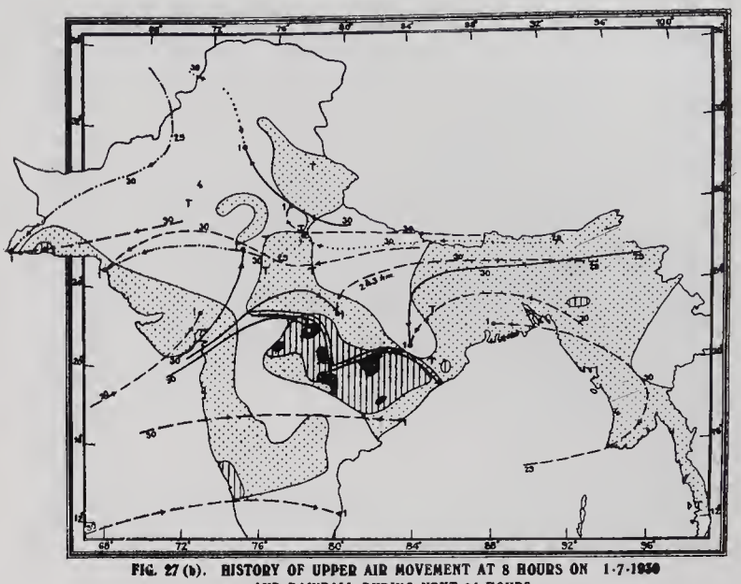


FIG. 27 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 1-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

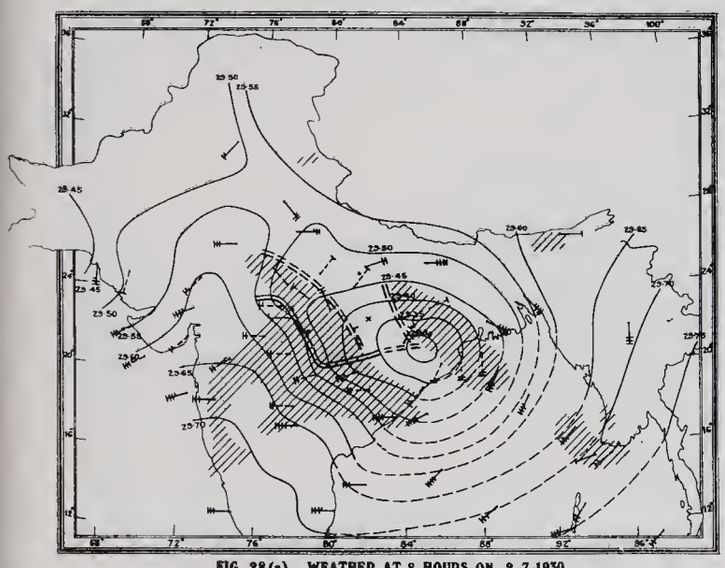


FIG. 28 (a). WEATHER AT 8 HOURS ON 2-7-1930.

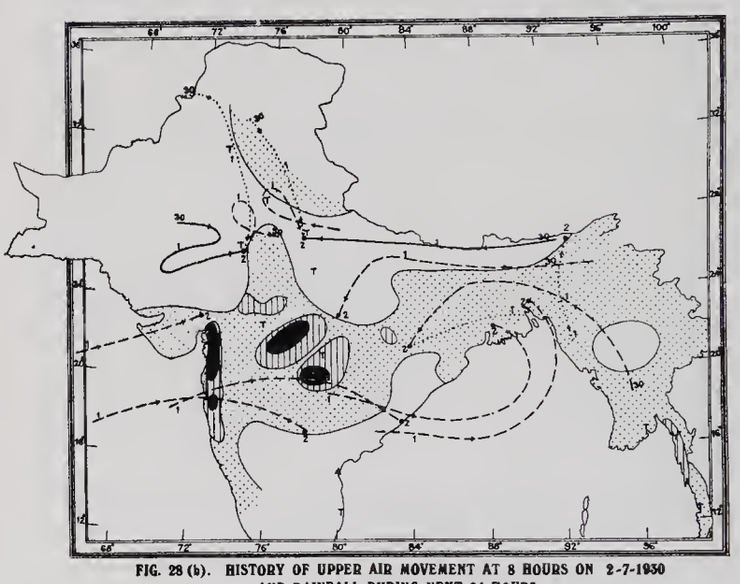


FIG. 28 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 2-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

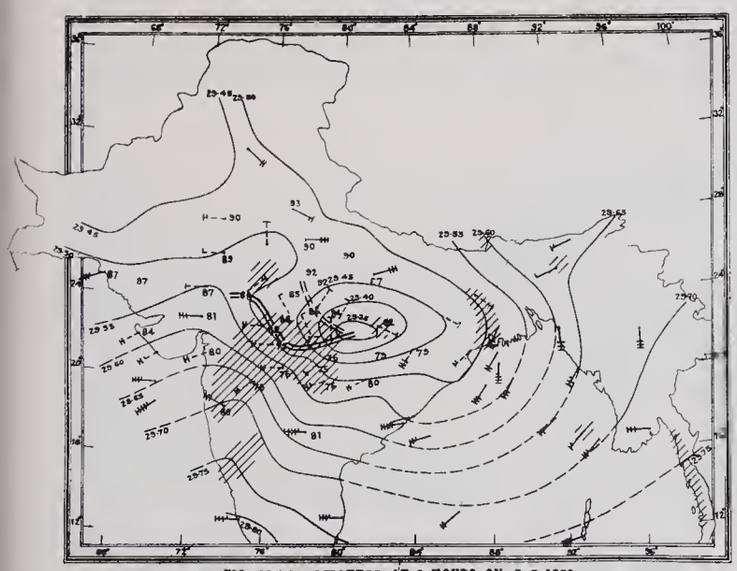


FIG. 29 (a). WEATHER AT 8 HOURS ON 3-7-1930.

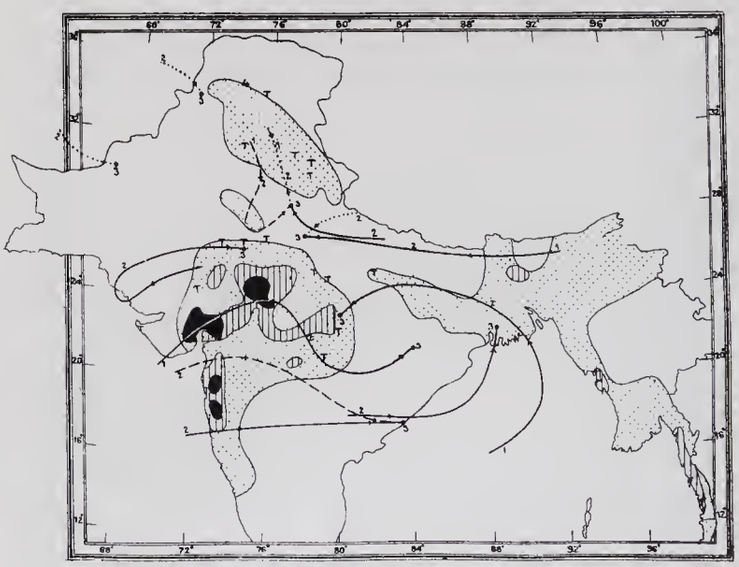


FIG. 29 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 3-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

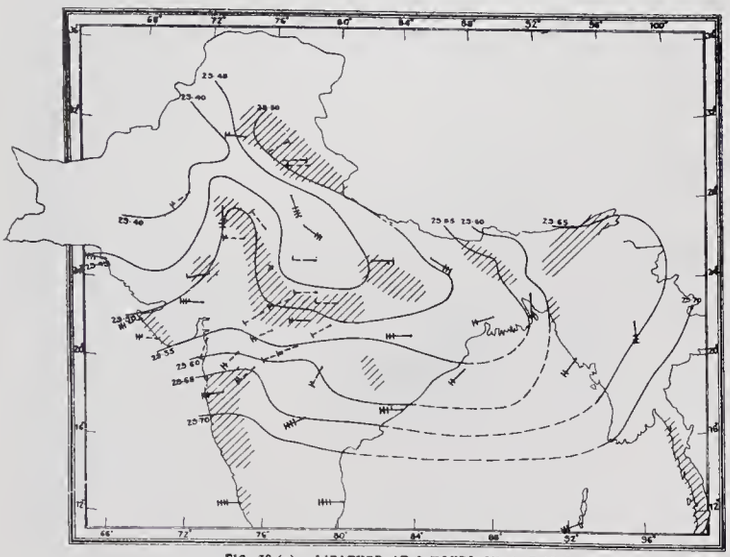


FIG. 30 (a). WEATHER AT 8 HOURS ON 4 -7-1930.

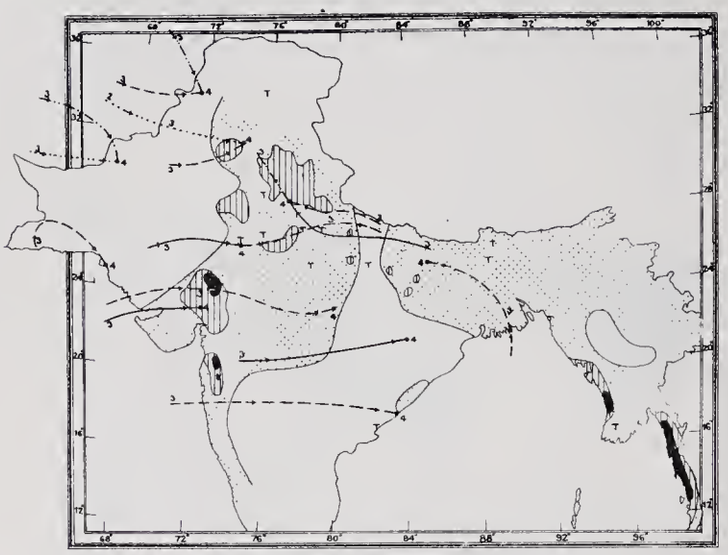


FIG. 30 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 4-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

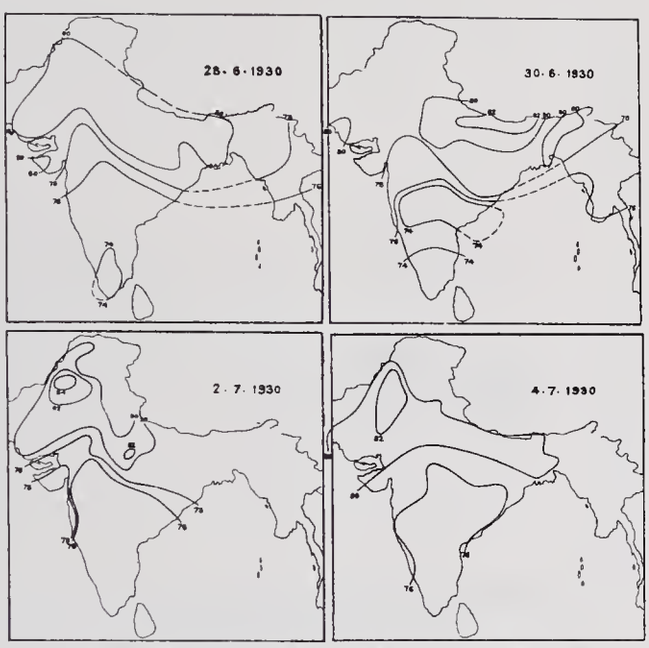


FIG. 31. DISTRIBUTION OF WET BULB TEMPERATURE IN °F ON 28 & 30-6-1930 & 2 & 4-7-1930 (REDUCED TO SEALEVEL ON THE ASSUMPTION THAT IT VARIES WITH HEIGHT AS THE CURVE OF SATURATION ADIABATIC).

FIG. 32. HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 13-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

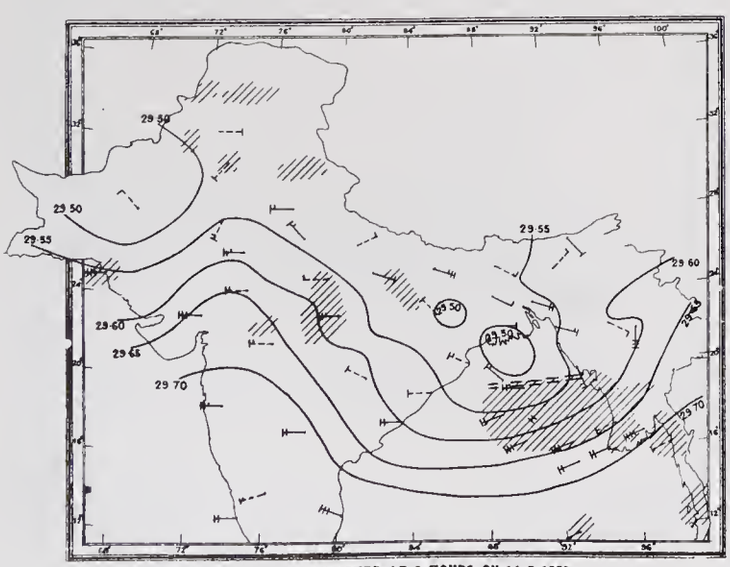


FIG. 33 (a). WEATHER AT 8 HOURS ON 14-7-1930.

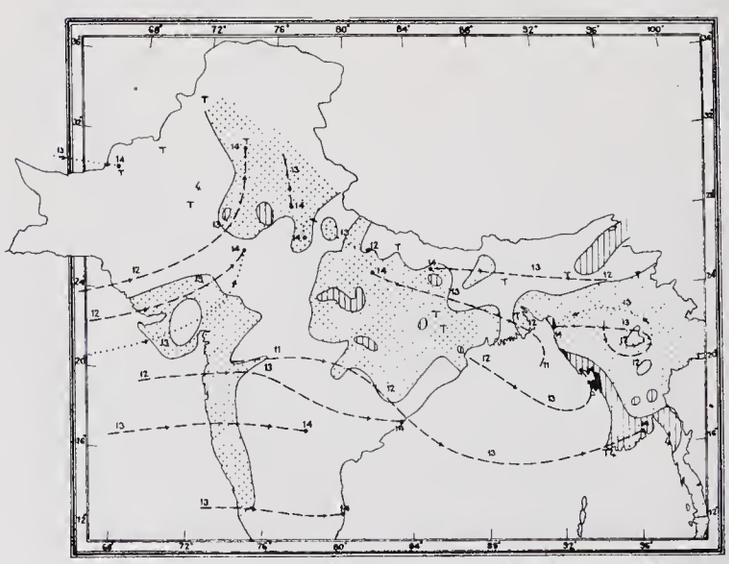


FIG. 33 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 14-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.R.Z.O. Poona, 1933.

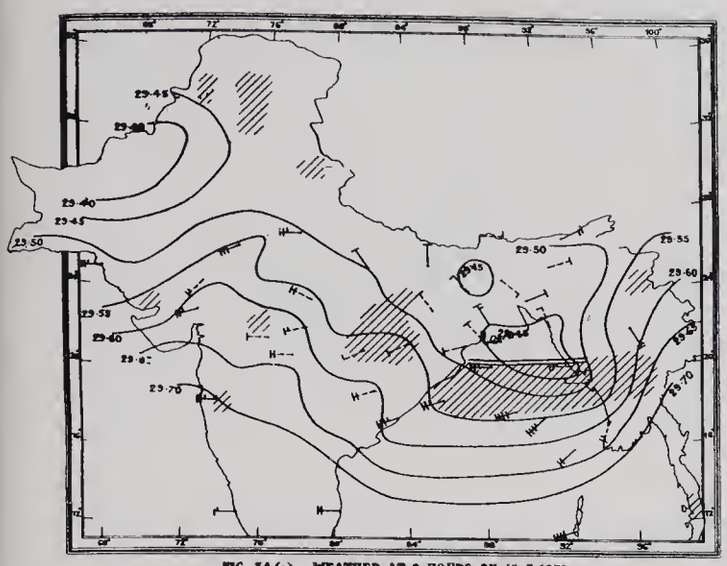


FIG. 34 (a). WEATHER AT 8 HOURS ON 16-7-1930

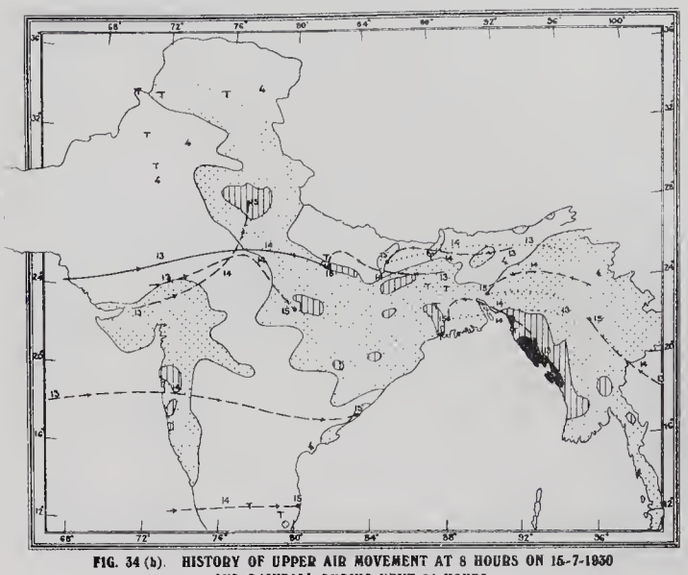


FIG. 34 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 16-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

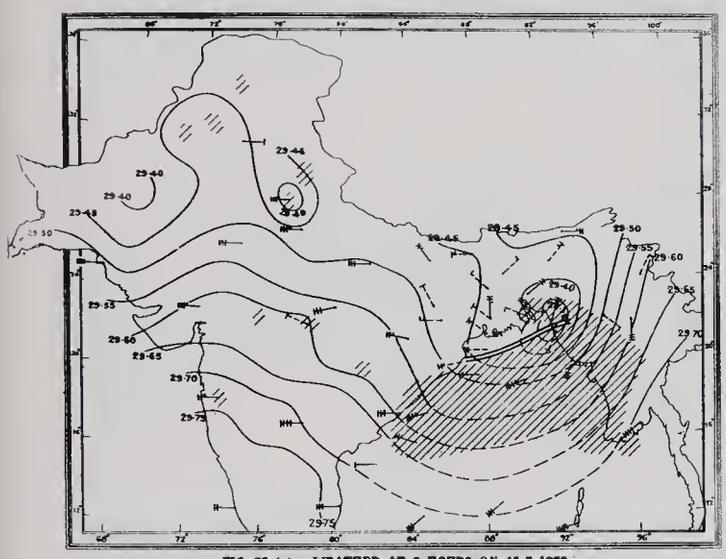


FIG. 35 (a). WEATHER AT 8 HOURS ON 16-7-1930.

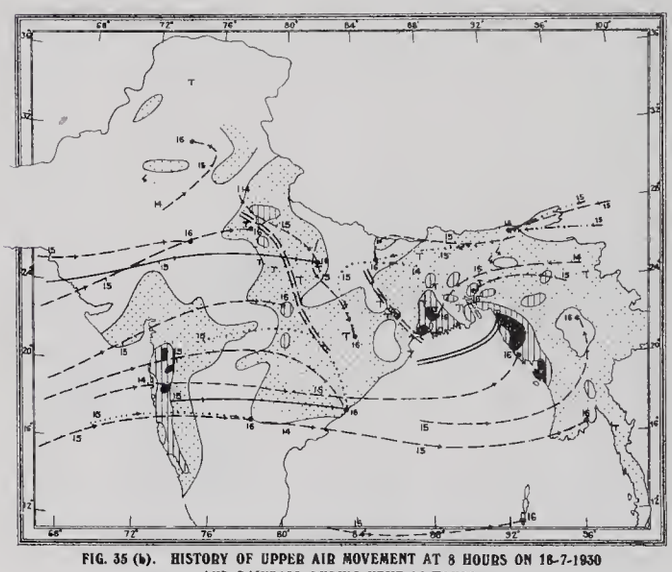


FIG. 35 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 16-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

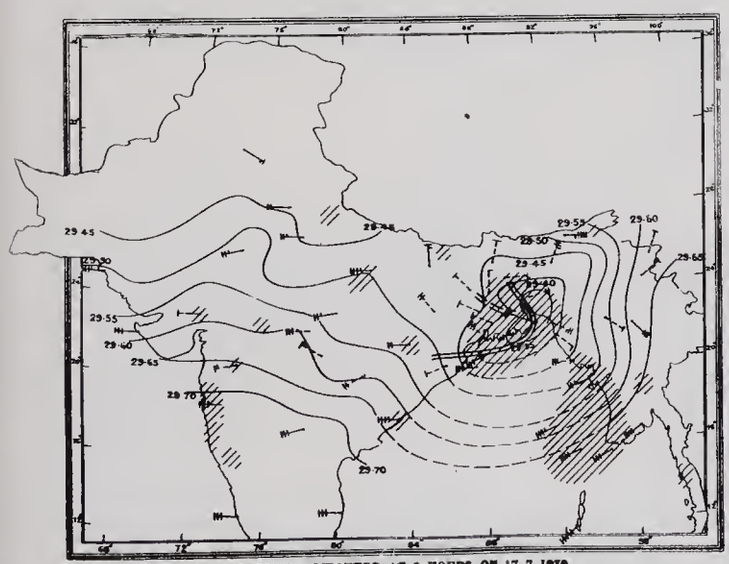


FIG. 36 (a). WEATHER AT 8 HOURS ON 17-7-1930.

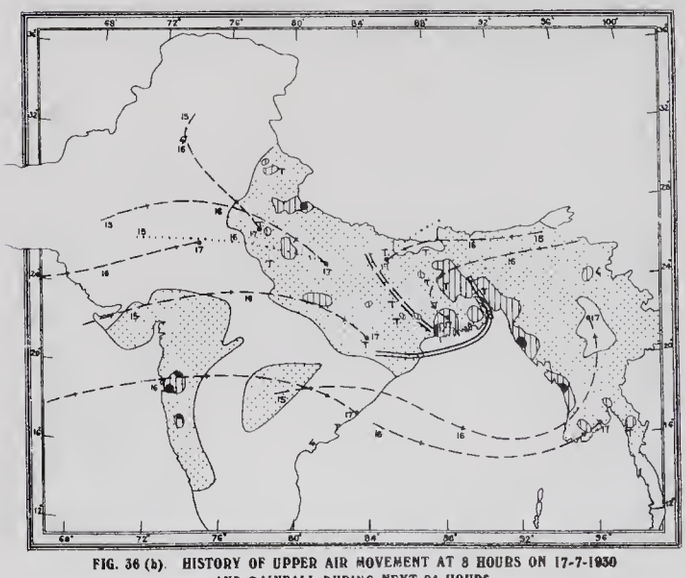


FIG. 36 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 17-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. POONA, 1933.

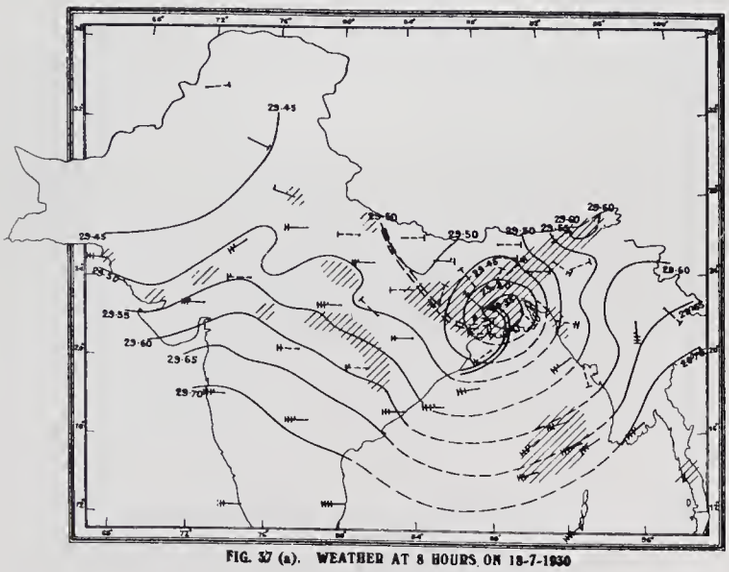


FIG. 37 (a). WEATHER AT 8 HOURS ON 18-7-1930

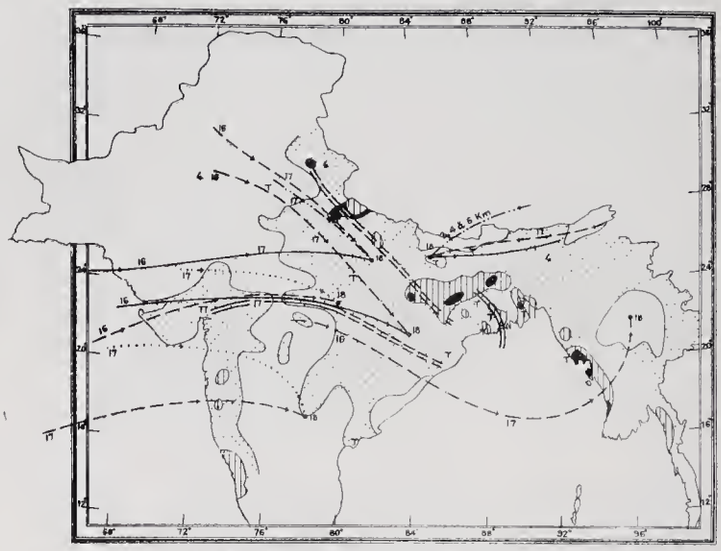


FIG. 37 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 18-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

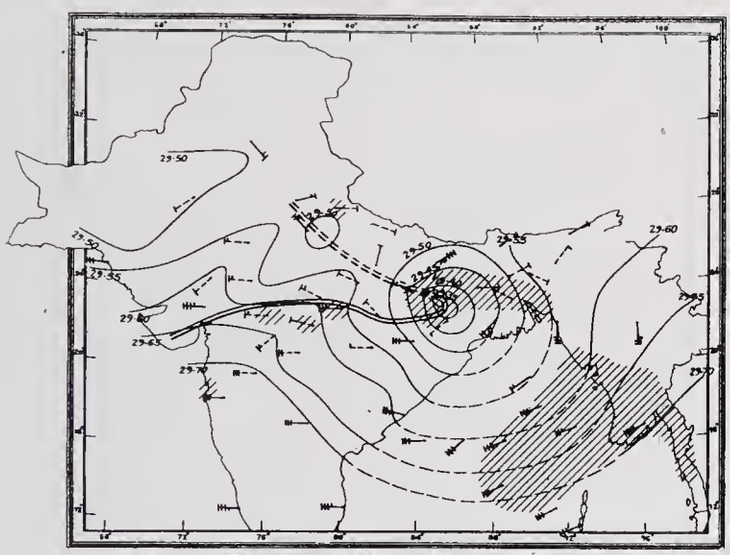


FIG. 38 (a). WEATHER AT 8 HOURS ON 19-7-1930

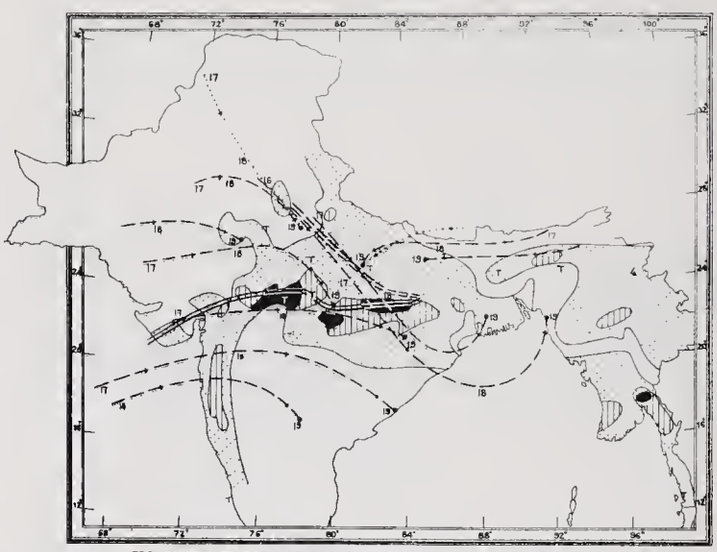


FIG. 38 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 19-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

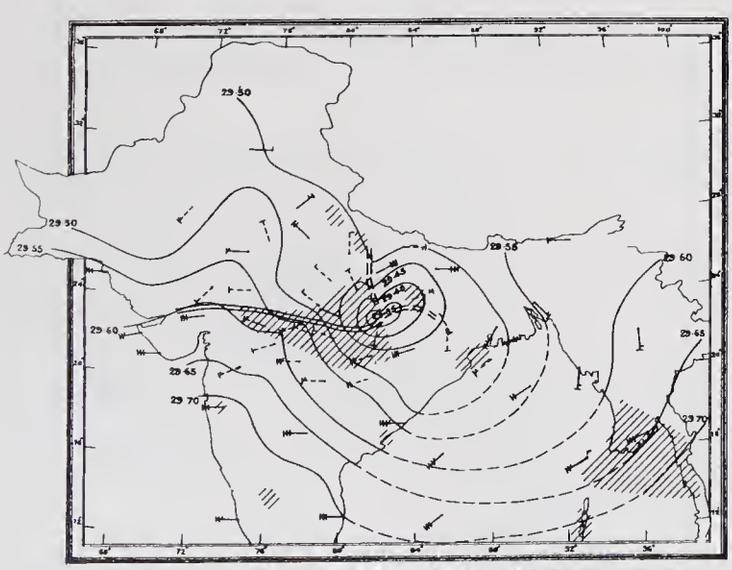


FIG. 39 (a). WEATHER AT 8 HOURS ON 20-7-1930

FIG. 39 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 20-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. POONA, 1933.

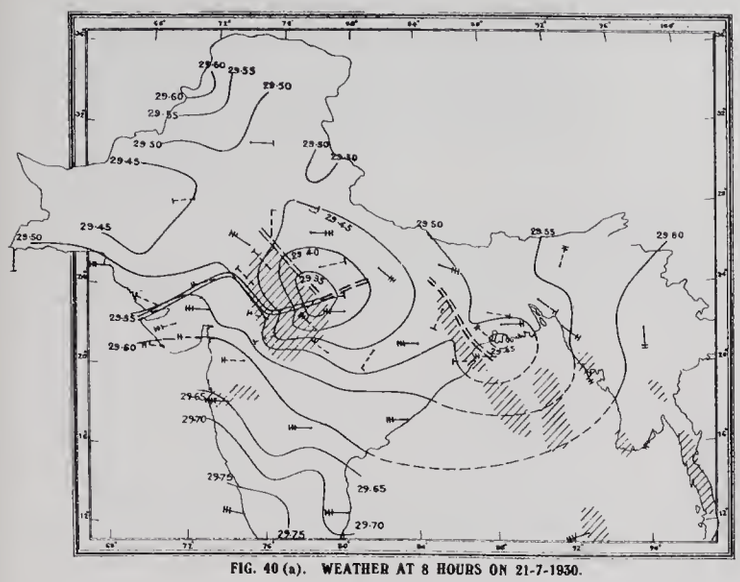


FIG. 40 (a). WEATHER AT 8 HOURS ON 21-7-1930.

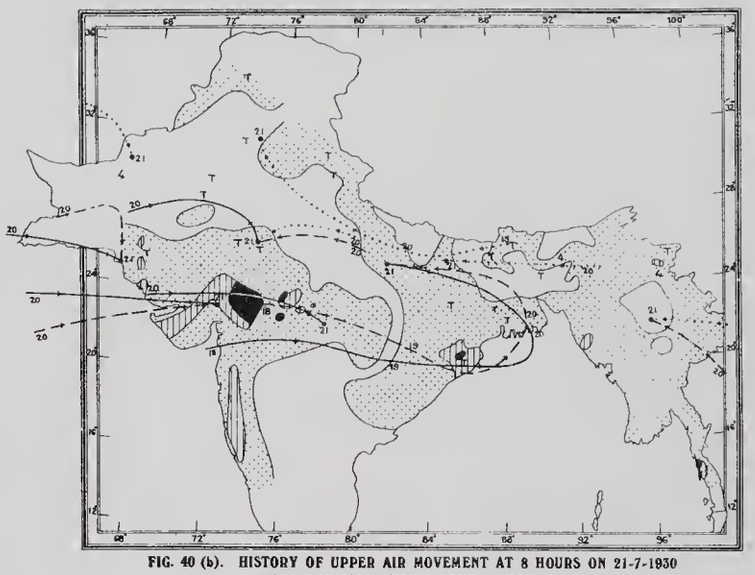


FIG. 40 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 21-7-1930 AND RAINFALL OURING NEXT 24 HOURS.

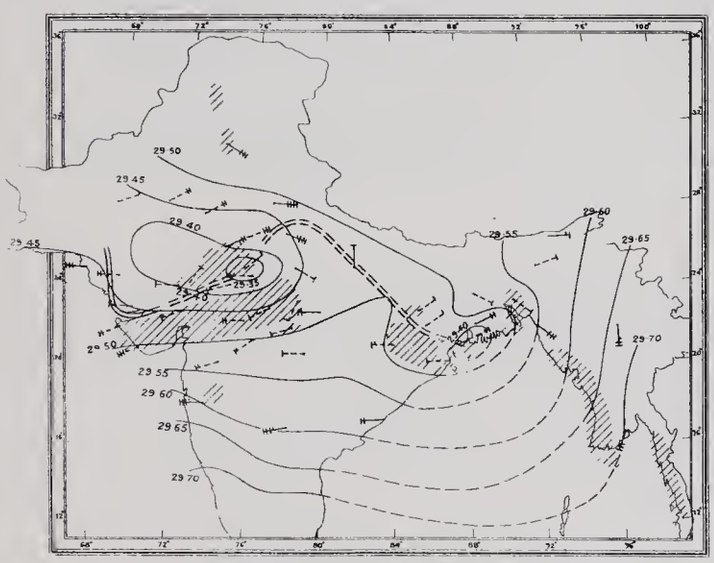


FIG. 41 (a). WEATHER AT 8 HOURS ON 22-7-1930.

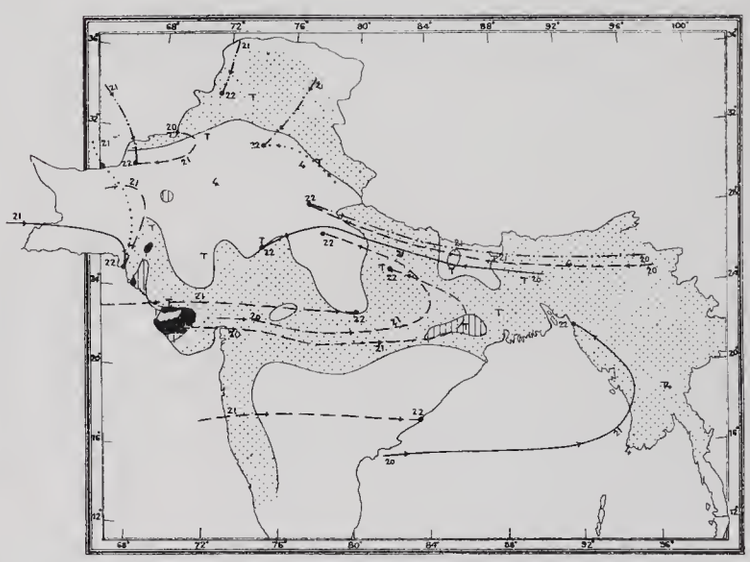


FIG. 41 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 22-7-1930 ANO RAINFALL OURING NEXT 24 HOURS.

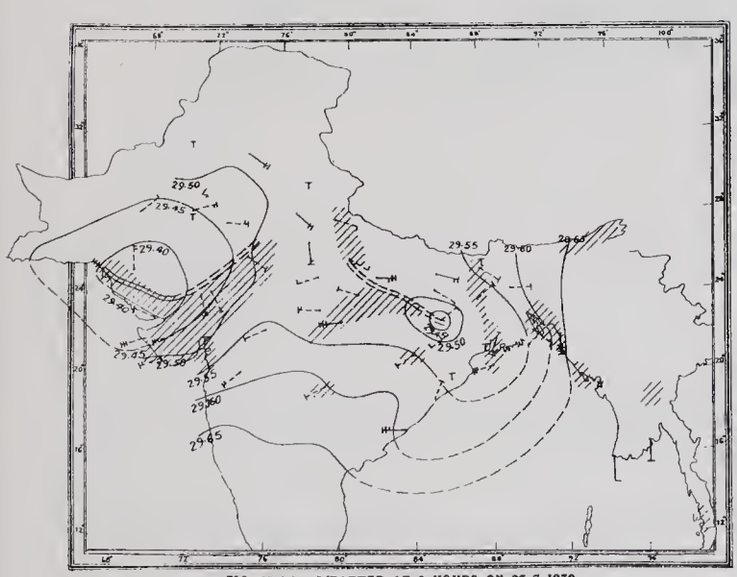


FIG. 42 (a). WEATHER AT 8 HOURS ON 23-7-1930.

FIG. 42 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 23-7-1930 ANO RAINFALL OURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

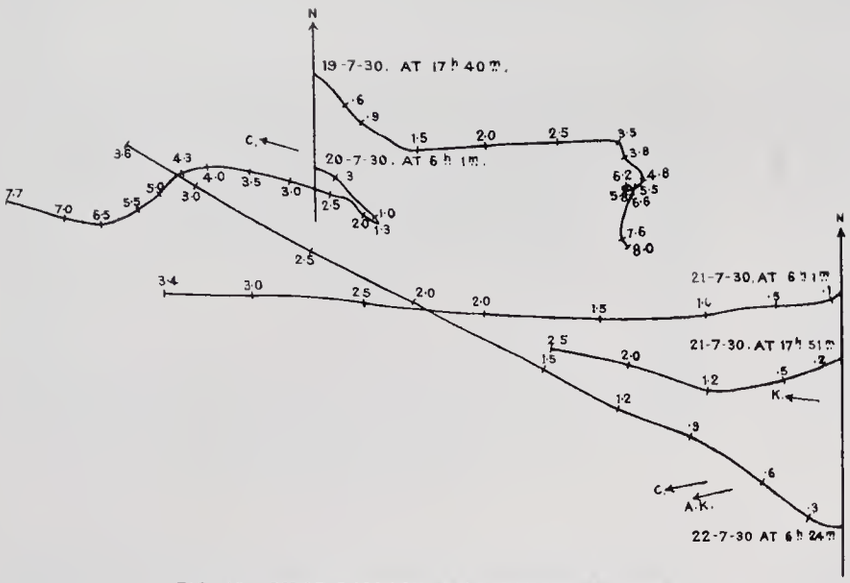


FIG. 43. PILOT BALLOON TRAJECTORIES AT AGRA.

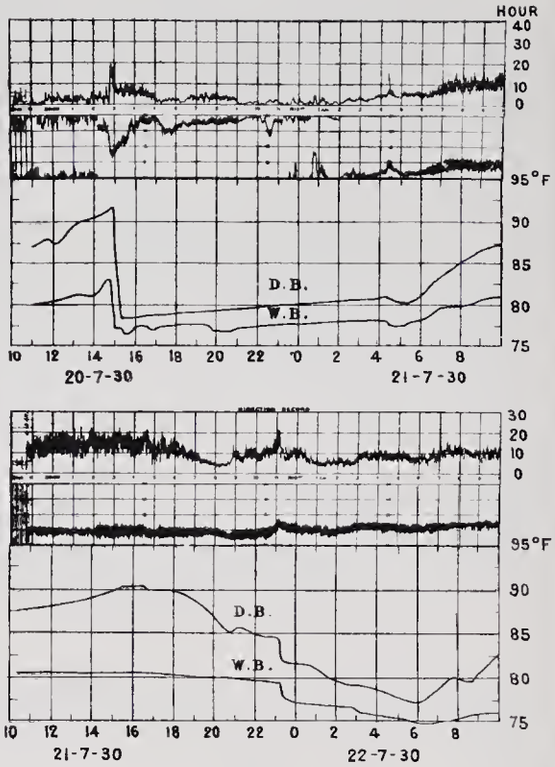


FIG. 44. WIND VELOCITIES & DIRECTIONS & DRY & WET BULB TEMPERATURES AT AGRA ON 20 TO 22-7-1930.

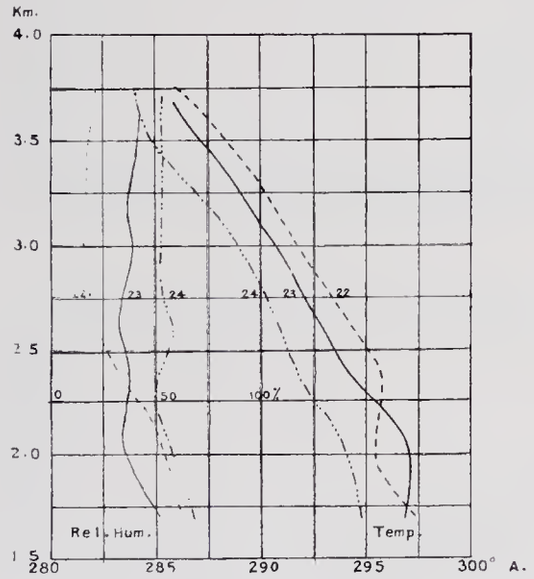


FIG. 45. UPPER AIR TEMPERATURES AND HUMIDITIES AT QUETTA ON 22, 23 & 24-7-1930. (EROPLANE ASCENTS)

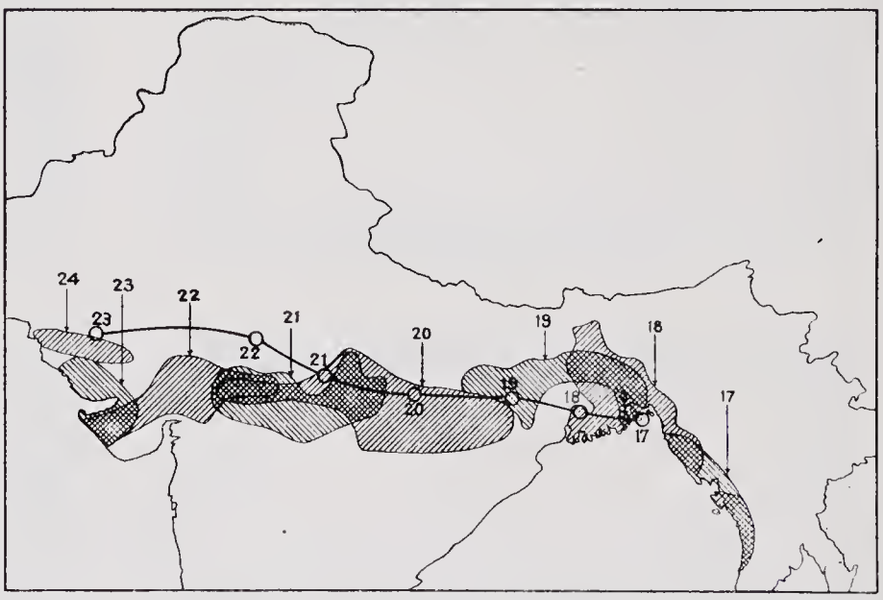

Chief areas of heavy rainfall during past 24 hrs. recorded at 8 hrs. on 17, 19, 21 & 23-7-1930
" " " " " " " " " " " " " 18, 20, 22 & 24-7-1930.
Positions of centre of depression at 8 hrs. on the respective dates.

FIG. 46. TRACK OF CENTRE OF LOW PRESSURE AND AREAS OF HEAVY RAINFALL ON EACH DAY FROM 17 TO 24-7-1930.

G.P.Z O. Poona, 1933.

DISCUSSION OF RESULTS OF SOUNDING BALLOON ASCENTS AT POONA AND HYDERABAD DURING THE PERIOD OCTOBER 1928 TO DECEMBER 1931

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(Received 18th November 1933.)

Summary.—The paper contains a discussion of the monthly mean values of temperature, humidity, pressure, and derived quantities like lapse-rate, density and potential temperature obtained from sounding balloon ascents at Poona and Hyderabad in the Deccan during the period October 1928 to December 1931. Mean monthly differences of pressure and temperature between the Deccan and Agra and between the Deccan and Batavia are also discussed in their relation to the general upper wind circulation. The types of transition from the troposphere to the stratosphere and their seasonal distribution are analysed. Observations on a few individual days with relevant notes on the weather situation are given to illustrate (*a*) the daily temperature differences at different levels between Agra and the Deccan and (*b*) the nature of the variation of humidity with height. Up-to-date normal winds from pilot balloon ascents are used in the clothes-line diagrams given with the mean monthly tephigrams.

1. Introduction.

In a previous Memoir[1], one of the authors has discussed the results of sounding balloon ascents made at Agra during the period March 1925 to July 1928. In October 1928, a few months after the opening of the new Meteorological Office at Poona, sounding balloon work was started in the Deccan and the present paper contains a discussion of the results obtained from the soundings during the next three years. The data of individual ascents have been published in the Upper Air Data, *Part 14*, of the India Meteorological Department.

The meteorographs employed were of the Dines type and the balloons generally of ' vulpro ' tissue. A few balloons were of India-rubber and were imported. The records were made on graphited glass plates and were worked out from enlarged drawings obtained by optical projection with a magnification of 40-50. The meteorographs, balloons and graphited glass plates were supplied by the Upper Air Observatory, Agra. The total number of records used in the present discussion is 143 of which 78 were obtained from ascents at Poona and 65 from Hyderabad in the Deccan. Their monthly distribution is shown in *Table 1.* (The reason for letting off the balloons from Hyderabad instead of from Poona during the months June to October was that, owing to the prevalence of easterly winds above 6 km. in this season, the balloons would be carried westwards and fall into the sea if let off from Poona.)

TABLE 1.

Month.	J	F	M	A	M	J	J	A	S	O	N	D	Total.
Poona 18° 32′ N.; 73° 51′ E.	12	15	7	5	8	1	3	0	2	5	7	13	78
Hyderabad 17°20′N.; 78°30′E.	..	..	..	..	..	4	10	10	21	15	5	..	65

Mem. Ind. Met. Dept. 26(4), 51–77, 1934.

All the instruments were let off between 17 hrs. and 19 hrs. (I. S. T.). It is therefore unlikely that, even at the top of the ascent, the records are affected by insolation. The numbers of records giving data up to different heights are shown in *Table 2*.

TABLE 2.

Height (gkm.).	10 or lower.	10·1 to 12.	12·1 to 14.	14·1 to 16.	16·1 to 18.	18·1 to 20.	20·1 to 22.	22·1 to 24.	24·1 to 26.	26·1 to 28.
Number . . .	143	130	125	122	110	66	31	8	5	1

It will be seen that nearly 75 per cent. of the balloons reached heights exceeding 16 dynamic kilometres. The greatest height reached was 28·1 gkm. on 3rd December 1931 and the lowest temperature recorded was 183°·0 A at 17 gkm. on 14th May 1930.

The units used are, as in the memoir on Agra results, millibars, degrees Centigrade+ 273, and dynamic kilometres (gkm.). When there were ascents both at Poona and at Hyderabad in a month, they have all been used in preparing the means for the month.

2. Temperature.

Table 3 shows the monthly and annual mean temperatures (see also *Fig. 1*). The number of observations and the standard deviations of temperature in each month and at each level are given in *Table 4*. The values of temperature are given for each half-km. step up to 3 gkm. and for each kilometre thereafter.

TABLE 3.—MEAN MONTHLY AND ANNUAL TEMPERATURES (°A).

Height (gkm.).	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Mean.	Range.
25	..	14·5	..	..	..	..	..	17·0	..	..	22·0	12·5	216·5	9·5
24	..	14·0	18·0	..	..	..	..	15·5	..	..	19·0	11·0	215·5	8·0
23	..	14·5	14·0	..	..	..	..	14·5	..	..	18·0	13·5	215·0	4·5
22	..	11·5	10·0	..	..	..	..	13·5	..	..	10·0	14·5	212·0	4·5
21	17·5	07·0	06·0	.	..	..	..	11·5	10·0	08·0	02·0	14·0	209·5	15·5
20	14·0	07·0	04·0	..	04·5	..	04·5	09·0	03·0	04·5	98·5	09·5	206·0	15·5
19	04·5	01·0	98·0	94·0	99·0	..	00·0	03·0	01·0	06·0	96·0	05·0	200·5	12·0
18	00·5	99·0	95·5	93·5	94·0	93·0	96·0	02·0	96·5	00·5	95·5	00·5	197·0	9·0
17	94·5	99·0	92·0	94·5	90·5	92·5	94·5	96·5	95·0	94·5	92·0	95·5	194·5	8·5
16	94·5	00·5	95·0	94·5	91·0	94·0	93·5	96·0	94·0	93·5	92·5	94·5	194·5	9·5
15	97·5	04·5	99·0	98·5	96·0	99·0	98·0	00·0	98·0	97·5	97·0	99·0	198·5	8·5
14	01·0	09·0	05·0	04·5	04·0	06·0	06·0	07·5	06·0	05·0	04·0	05·0	205·5	8·0
13	09·0	16·0	12·0	09·0	14·0	15·5	14·5	16·0	14·5	13·0	12·5	12·0	213·0	7·0
12	18·0	23·0	20·0	18·5	22·0	24·0	23·0	23·5	23·0	21·5	21·0	20·0	221·5	6·0
11	26·0	30·0	27·0	26·5	30·0	32·0	31·5	32·0	31·5	30·0	29·5	28·0	229·5	6·0
10	35·0	37·5	35·0	35·0	38·0	39·5	40·0	39·5	39·5	38·5	38·0	35·5	237·5	5·0
9	42·5	44·5	43·0	43·5	46·0	48·0	47·5	47·0	47·5	46·0	46·0	43·0	245·5	5·5
8	49·5	51·0	50·5	50·0	53·5	55·0	55·0	55·0	54·5	53·5	53·5	51·0	252·5	5·5
7	56·5	58·0	58·5	57·5	60·5	61·5	61·5	61·0	61·5	59·5	60·0	59·0	259·5	5·5
6	63·0	63·5	64·5	63·5	67·0	67·5	66·5	67·0	67·0	66·0	66·0	64·5	265·5	4·5
5	69·5	69·0	70·5	69·5	72·0	73·5	72·5	73·0	72·5	72·0	72·0	71·0	271·5	4·0
4	76·0	75·5	74·5	76·0	78·0	79·5	78·0	77·0	78·0	78·0	77·5	76·5	277·0	5·0
3	80·5	82·0	81·5	84·0	85·5	86·0	83·5	82·5	83·5	82·5	83·0	80·5	283·0	5·5
2·5	82·5	85·5	86·5	89·0	89·0	89·0	86·0	85·0	86·5	85·5	84·5	82·5	286·0	6·5
2	86·5	90·0	91·5	93·5	93·5	91·5	89·0	89·0	89·0	88·0	87·0	86·0	289·5	7·5
1·5	91·0	94·5	96·0	98·0	97·0	96·5	92·5	92·0	92·5	92·0	91·5	90·0	293·5	7·0
1	96·0	99·0	99·5	03·0	02·0	00·5	95·5	95·0	96·5	96·0	95·0	94·0	297·5	8·5
SURFACE (0·54)	00·5	03·0	04·5	06·0	06·0	03·5	99·5	01·0	99·5	99·0	00·0	97·5	301·5	9·0

N.B.—The hundreds figure has been omitted except in the annual means.

TABLE 4.—STANDARD DEVIATIONS OF TEMPERATURES, WITH NUMBER OF OBSERVATIONS.

Height (gkm.).	January.		February.		March.		April.		May.		June.		July.		August.		September.		October.		November.		December.	
	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ	n	σ
20	2	1·0	8	7·6	2	1·2	..	..	3	1·8	..	..	1	0	5	1·9	2	3·5	1	0	2	2·5	5	4·4
19	6	6·4	11	8·3	3	2·6	2	1·1	3	2·4	..	..	1	0	6	4·7	3	4·1	3	4·5	3	5·2	6	4·7
18	6	4·7	14	7·1	4	2·1	3	2·2	5	2·9	2	1·8	2	0·8	8	6·6	3	5·5	8	6·7	4	4·6	9	4·0
17	8	5·0	15	5·8	5	4·0	3	0·7	5	4·6	3	2·2	4	2·9	9	5·9	9	3·9	15	5·0	4	2·9	9	3·1
16	10	4·6	15	5·3	7	4·3	4	5·0	5	5·3	4	1·5	7	3·0	9	4·4	16	4·0	16	3·4	7	2·8	9	4·2
15	10	4·4	15	4·1	7	4·6	5	6·8	6	4·7	4	1·8	9	3·3	10	5·0	16	4·5	17	3·1	7	2·9	10	4·3
14	11	5·1	15	3·0	7	3·6	5	5·1	6	3·0	4	2·0	9	3·1	10	4·8	18	3·8	17	4·2	8	2·8	11	4·0
13	11	4·8	15	2·5	7	2·9	5	4·3	6	2·5	4	2·3	9	2·6	10	4·6	19	3·6	17	3·9	8	2·5	11	4·0
12	11	3·5	15	3·9	7	2·6	5	3·5	6	2·2	4	1·8	9	2·1	10	3·5	19	2·7	18	3·2	9	2·5	11	3·1
11	12	3·8	15	3·7	7	2·0	5	3·2	6	1·9	4	1·8	10	2·1	10	3·4	19	2·1	18	2·8	9	2·5	12	2·9
10	12	3·3	15	3·8	7	2·4	5	3·6	6	1·6	4	1·8	11	1·9	10	2·7	19	2·0	18	2·5	10	2·5	12	2·4
9	12	2·6	15	3·6	7	2·0	5	3·4	7	1·2	4	1·7	11	1·9	10	3·0	21	2·0	18	2·0	10	2·3	12	2·3
8	12	3·5	15	2·9	7	1·9	5	2·8	8	1·1	4	1·3	13	1·7	10	2·6	21	1·9	18	1·9	10	1·9	12	2·5
7	12	2·5	15	2·4	7	1·6	5	3·4	8	1·8	4	1·4	13	1·3	10	2·2	21	1·6	19	1·8	11	1·0	12	2·9
6	12	2·1	15	1·8	7	1·0	5	3·3	8	1·5	5	2·5	13	1·6	10	1·6	21	1·5	19	1·7	11	1·2	13	1·6
5	12	1·8	15	1·4	7	2·2	5	2·3	8	1·7	5	2·1	13	0·9	10	1·2	22	1·4	20	1·4	11	1·2	13	1·8
4	12	2·0	15	1·5	7	1·7	5	1·4	8	2·0	5	1·9	13	1·0	10	1·4	23	1·6	20	1·6	11	1·5	13	1·6
3	12	1·6	15	1·9	7	1·5	5	1·2	8	2·7	5	1·8	13	1·2	10	1·5	23	1·2	20	1·8	11	1·1	13	2·1
2	12	1·3	15	3·0	6	2·4	5	1·3	8	2·8	5	3·0	13	1·3	10	1·5	23	1·7	20	1·8	11	1·7	13	1·7
1	12	1·8	15	2·8	6	2·2	3	0·7	5	3·7	4	2·2	8	1·6	7	1·5	22	1·1	19	2·3	10	1·2	13	1·5

[*N.B.*—n=number of observations; σ=standard deviation.]

Seasonal mean temperatures are given in *Table 5*. For the purpose of this Table, (and also for *Table 8*), the year has been divided into four seasons as follows :—

(*a*) *Cold season.*—November, December, January and February.

(*b*) *Hot season.*—March, April and May.

(*c*) *Monsoon season.*—June, July, August and September, and

(*d*) *Post-monsoon* (*transition*) *season.*—October.

This division is slightly different from the one adopted in the memoir on Agra results, but owing to climatological differences between Poona and Agra, the difference is unavoidable.

TABLE 5.—SEASONAL MEAN TEMPERATURES.

Height (gkm.).	Temperatures (°A).				Height (gkm.).	Temperatures (°A).			
	November, December, January and February.	March, April and May.	June, July, August and September.	October.		November, December, January and February.	March, April and May.	June, July, August and September.	October.
20	207·5	204·5	205·5	204·5	10	36·5	36·0	39·5	38·5
19	02·2	197·0	01·5	06·0	9	44·0	44·0	47·5	46·0
18	199·0	94·0	197·0	00·5	8	51·5	50·5	55·0	53·5
17	95·5	92·5	94·5	194·5	7	58·5	59·0	61·5	59·5
16	95·5	93·5	94·5	93·5	6	64·0	65·0	67·0	66·0
					5	70·5	70·5	73·0	72·0
					4	76·5	76·0	78·5	78·0
					3	81·5	84·0	84·0	82·5
15	99·5	98·0	98·5	97·5	2·5	84·0	88·0	86·5	85·5
14	205·0	204·5	206·5	205·0	2	87·5	93·0	89·5	88·0
13	12·5	11·5	15·0	13·0	1·5	91·5	97·0	93·5	92·0
12	20·5	20·0	23·5	21·5	1	96·0	301·5	97·0	96·0
11	28·5	28·0	31·5	30·0					
					Surface (0·54)	300·0	05·5	301·0	99·0

The lowest temperature at all levels up to 14 gkm. occurs in the winter months December and January. The high values of temperature between 12 and 18 gkm. in February should be considered abnormal. The highest temperatures near the surface and up to 2 gkm. occur in April to May and shift over to June between 3 and 6 gkm. The high temperatures from the surface to 3 gkm. during April to June are due mainly to ground heating by insolation. From June to July, with the setting in of the monsoon there is a sharp drop in temperature at all levels up to 4 gkm. and the lower temperature continues during the rest of the year with a feeble maximum in September-October. In the months May to September, there is a flat maximum of temperature between the levels 5 and 14 gkm. This is partly caused by the liberation of heat in the atmosphere due to thunderstorm rain in May and monsoon rain in the other months. As the observations between June and September refer to Hyderabad and as the upper winds above 5 or 6 gkm. are invariably from the east, the rainfall causing the heating must be that which occurs in the Bay of Bengal, Burma and Indo-China. The seasonal variation of temperature is a maximum at the surface and decreases with height to a minimum at 5 gkm. It remains comparatively small from 5 to 12 gkm. and increases again thereafter. The secondary maximum of seasonal variation shown by Agra temperatures at 10 gkm. does not appear here.

The remarkably small variability of temperature in all the months of the year (*Table 4*) gives an estimate of the significance of the means.

3. Lapse-rates.

In discussing lapse-rates near the ground, it has to be remembered that the data refer to evening hours, generally half to one hour before sun-set and do not all refer to the same place. During July, August and part of September, low and middle clouds are very common. *Table 6* shows the mean lapse-rates in each month of the year; and *Table 7* the seasonal mean lapse-rates (see also *Fig. 2*). Seasonal frequencies of lapse-rates are given in *Table 8*. It will be seen that the most frequent values of lapse-rate occurring in any season are more or less the same as the mean lapse-rates for the season. The day to day variation of lapse-rates is largest in winter and smallest in the monsoon.

TABLE 6.—MEAN MONTHLY LAPSE-RATES (IN °C PER DYNAMIC KILOMETRE).

Layer (gkm.).	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual mean.
20—19	—3·3	—5·1	—7·3	..	—5·6	..	—4·5	—4·1	—3·8	—4·6	—6·0	—5·3	—5·0
19—18	—4·2	—1·3	—2·3	—1·5	—5·2	..	—5·0	—3·4	—4·3	—5·0	—2·6	—5·1	—3·6
18—17	—4·3	0·1	—1·5	1·5	—3·6	—1·6	—1·3	—6·3	—3·7	—5·2	—3·3	—4·3	—2·8
17—16	0·2	1·4	3·5	2·4	0·7	1·8	0·0	—0·4	0·0	—0·7	0·1	—1·0	0·7
16—15	3·2	3·7	4·1	3·8	5·5	5·2	4·7	4·7	3·9	4·4	4·7	5·1	4·4
15—14	3·5	4·8	6·1	6·2	8·4	7·1	7·9	7·8	8·2	7·1	7·1	6·0	6·7
14—13	8·0	7·1	6·9	5·4	9·7	9·3	8·8	8·5	8·9	8·5	8·3	7·1	8·0
13—12	9·1	7·0	7·7	8·5	8·2	8·7	8·6	7·8	8·6	8·6	8·7	8·0	8·3
12—11	8·9	7·3	7·4	8·2	7·6	8·0	8·6	8·0	8·7	8·5	8·5	8·4	8·2
11—10	9·0	7·4	8·0	8·5	8·1	7·5	8·7	7·4	8·2	8·1	8·4	7·7	8·1
10—9	7·7	6·9	7·9	8·4	8·3	8·5	7·6	8·1	7·7	7·6	7·9	7·2	7·8
9—8	7·1	6·8	7·4	6·7	7·1	6·7	7·1	7·8	7·0	7·5	7·5	7·9	7·2
8—7	6·6	6·6	7·9	6·4	7·0	6·5	6·5	6·2	6·8	6·5	6·3	8·0	6·8
7—6	6·6	5·5	6·1	5·8	6·7	5·1	5·0	6·0	5·8	6·3	6·0	5·9	5·9
6—5	6·9	5·7	6·3	6·2	4·8	5·8	6·1	5·9	5·5	6·0	6·1	6·3	5·9
5—4	6·1	6·2	3·7	6·5	6·0	6·3	5·6	4·7	5·6	5·8	5·6	5·5	5·6
4—3	4·9	6·6	7·3	8·1	7·8	6·3	5·3	4·5	5·3	4·9	4·9	3·8	5·8
3—2·5	3·8	7·5	8·3	9·6	8·0	5·9	5·2	5·5	5·6	5·5	3·1	4·6	6·1
2·5—2	8·0	8·6	10·2	9·0	8·2	5·6	5·5	6·9	5·8	5·5	5·9	7·0	7·2
2—1·5	8·9	9·0	8·7	8·1	7·0	7·9	5·9	7·0	7·0	6·9	7·9	7·7	7·9
1·5—1	9·2	9·6	7·4	8·8	8·8	8·4	6·7	8·1	7·1	7·7	7·6	8·3	8·1

Table 7.—Seasonal Mean Lapse-rates.

Layer (gkm.).	Lapse-rates (°C/gkm.).				Layer (gkm.).	Lapse-rates (°C/gkm.).			
	November, December, January and February.	March, April and May.	June, July, August and September.	October.		November, December, January and February.	March, April and May.	June, July, August and September.	October.
20—19	—4·9	—6·5	—4·1	—4·6	**10—9**	7·4	8·2	8·0	7·6
19—18	—3·3	—3·0	—4·2	—5·0	9—8	7·3	7·1	7·1	7·5
18—17	—2·9	—1·2	—3·2	—5·2	8—7	6·9	7·1	6·5	6·5
17—16	0·2	2·2	0·3	—0·7	7—6	6·0	6·2	5·5	6·3
16—15	4·2	4·5	4·6	4·4	6—5	6·3	5·8	5·8	6·0
					5—4	5·9	5·7	5·5	5·8
15—14	5·3	6·9	7·7	7·1	4—3	5·1	7·7	5·3	4·9
14—13	7·6	7·3	8·9	8·5	3—2·5	4·7	8·6	5·5	5·5
13—12	8·2	8·1	8·4	8·6	2·5—2	7·4	9·1	5·9	5·5
12—11	8·3	7·7	8·3	8·5	2—1·5	8·4	7·9	6·9	6·9
11—10	8·1	8·2	7·9	8·1	1·5—1	8·7	8·3	7·6	7·7

Table 8.—Seasonal Frequencies of Lapse-rates.

Layer (gkm.).	Range of Lapse-rates.									
	<—3·9	—3·9 to —2·0	—1·9 to 0	0·1 to 2·0	2·1 to 4·0	4·1 to 6·0	6·1 to 8·0	8·1 to 10·0	>10·0	Total No. of Obsns.
(a) November, December, January and February.										
19—20	9	7								16
18—19	10	5	5	3	1					24
17—18	12	6	5	5	1	1	1			31
16—17	6	2	10	5	7	7				37
15—16			2	3	19	12	3	3		42
14—15			1	4	9	13	10	6		43
13—14					4	10	15	11	6	46
12—13				1	1	5	12	23	4	46
11—12					1	1	21	22	1	46
10—11						3	18	27	1	49
9—10				1	2	4	26	17		50
8—9					1	9	24	16		50
7—8				1	2	10	24	13		50
6—7				1	3	21	23	3		51
5—6					2	24	20	6		52
4—5					2	27	22	1		52
3—4				3	10	25	11	3		52
2·5—3	1		3	6	7	16	10	9		52
2—2·5			1		3	11	15	18	4	52
1·5—2						3	19	25	4	51
1—1·5					2	2	16	18	11	49

TABLE 8.—SEASONAL FREQUENCIES OF LAPSE-RATES—*contd.*

Layer (gkm.)	Range of Lapse-rates.									Total No. of Obsns.
	<—3·9	—3·9 to —2·0	—1·9 to 0	0·1 to 2·0	2·1 to 4·0	4·1 to 6·0	6·1 to 8·0	8·1 to 10·0	>10·0	
(b) March, April and May.										
19—20	4	1								5
18—19	2	4	2							8
17—18	3	1	5	2	1					12
16—17		1	1	3	6	2				13
15—16			1	1	3	9	1	1		16
14—15					1	7	5	3	2	18
13—14					2	4	4	4	4	18
12—13							10	7	1	18
11—12						1	11	6		18
10—11						1	9	6	2	18
9—10							10	6	2	18
8—9						5	9	5		19
7—8						3	11	6		20
6—7						7	13			20
5—6				1	3	8	6	2		20
4—5				2	4	6	6	2		20
3—4						4	7	9		20
2·5—3				1		1	4	13	1	20
2—2·5							6	9	4	19
1·5—2					1	3	5	6	2	17
1—1·5						2	3	6	1	12
(c) June, July, August and September.										
19—20	4	4								8
18—19	4	4	1	1						10
17—18	11	1	1	2						15
16—17	3	5	6	4	6	1				25
15—16		1	2	3	9	12	5	3	1	36
14—15					1	6	15	14	3	39
13—14						1	12	21	7	41
12—13							16	23	2	41
11—12							16	23	2	41
10—11						1	21	20		42
9—10						1	25	16	1	43
8—9						3	36	6		45
7—8						11	32	3		46
6—7				1	3	29	14			47
5—6					2	28	17	1		48
4—5					6	26	16	1		49
3—4					10	26	13	1		50
2·5—3		1			9	25	13	2	1	51
2—2·5			1	6	1	18	19	4	1	50
1·5—2			1		3	14	18	9	3	48
1—1·5					5	7	13	11	3	39
(d) October.										
19—20	1									1
18—19	2	1								3
17—18	5	2			1					8
16—17	5	2		4	3	1				15
15—16		1	3		1	5	3	3		16
14—15				1	1	1	7	7		17
13—14							4	12	1	17
12—13							4	12	1	17
11—12							5	13		18
10—11							9	9		18
9—10						1	15	2		18
8—9						3	11	4		18
7—8						5	12	1		18
6—7						9	10			19
5—6					1	9	9			19
4—5					1	11	8			20
3—4			1	1	3	9	6			20
2·5—3	1				2	10	4	3		20
2—2·5	1			2	1	8	5	2	1	20
1·5—2					2	3	10	5		20
1—1·5					2	2	6	5	4	19

In November, December and January, the lapse-rate is high up to 2·5 gkm. and this is followed by a region of small lapse-rates which in individual cases extends to 4 gkm. Analysis of the sources of air supply in this season shows that, while the air both above and below this region has ultimately its origin in the westerly zonal circulation of north-west India, the air below 2 km. over Poona has had a longer travel over land, skirting over the seasonal high pressure area which lies over Central India and the Central Provinces, and thus has had the opportunity of becoming surface-heated by day. In this connection, it has to be remembered that ground heating by day and ground cooling by night cannot produce exactly contrary effects. Ground cooling promotes stratification and is confined to the layer near the surface not exceeding half a kilometre in thickness while ground heating increases the lapse-rate and promotes mixing up of the layers. In the hot season months, March and April, the region of high lapse-rates extends upwards. In May also high lapse-rates generally extend to 4 gkm., but, owing to the effect of occasional thunderstorm rains, the lapse-rates tend to get smaller. In Agra during April and May high lapse-rates extend to 4—5 gkm. Instances of super-adiabatic lapse-rates in the lower layers (up to 2·5 gkm.) occur in all the seasons, but are rare in the monsoon.

In *Table 9* are given the frequencies of lapse-rates above 15 gkm. irrespective of season. The results of 39 ascents in 1932 have also been added in preparing this table.

TABLE 9.—FREQUENCIES OF LAPSE-RATES IRRESPECTIVE OF SEASON ABOVE 15 GKM.

Layer (gkm.).	<—9·9	—9·9 to —8·0	—7·9 to —6·0	—5·9 to —4·0	—3·9 to —2·0	—1·9 to 0	0·1 to 2·0	2·1 to 4·0	4·1 to 6·0	6·1 to 8·0	8·1 to 10·0	>10·0
28—29						1						
27—28						2						
26—27						2						
25—26						2						
24—25					1	4						
23—24				1	2	3						
22—23			2	2	1	3		1				
21—22		2	1	2	1	4						
20—21		1	2	5	11	3						
19—20	3		8	13	17							
18—19	1		10	20	20	11	4	1				
17—18	2	6	9	19	15	18	11	4	4	1		
16—17			2	16	12	21	19	31	15			
15—16				1	2	9	9	39	50	19	12	1

In all seasons, the region 10—14 gkm. is characterised by high lapse-rates. Over Agra high lapse-rates at these levels generally occur in the months May to October. The existence of a layer of high lapse-rates in the upper part of the troposphere has been explained [2, 3] as being due to a rapid change with height of the net loss of energy by radiation from the water-vapour present in those layers. Lapse-rates slightly more than the dry adiabatic and extending over a thickness of 1—2 gkm. are not uncommon at these levels; they are not confined to any particular season.

4. The Tropopause.

There is invariably a permanent inversion over Poona or Hyderabad which usually lies between 16 and 18 gkm. and which may be considered to be the " tropopause ". Its

mean height is 16·6 gkm. and mean temperature 192°·5A. Above the tropopause, as in other places in the tropics, the temperature increases with height and reaches a value of about 217°A at 24 gkm. The rate of increase is largest immediately above the tropopause and gradually decreases with height. We cannot form any definite conclusion regarding the seasonal variation of temperature in the stratosphere, except that it is small.

In the department's annual publication of Indian sounding balloon data and in the discussion of Agra soundings, the nature of the transition from the troposphere to stratosphere is classified into four types,—types I, II and III of which are defined according to the same conventions as those in use in the London Meteorological Office. Type IV is a composite type in which the transition from troposphere to stratosphere takes place in two stages. A further examination of the data shows that with a slightly extended meaning, the composite type of transition is much more common than it was originally considered to be. At Agra, in the composite type of transition which takes place in two stages and occurs fairly frequently in the months November to April with the lower transition at 12—13 gkm. and the upper at 16—18 gkm., the lower transition is usually a sharp decrease of lapse-rate sometimes getting to isothermal above the transition and extending over a thickness of 2—5 gkm. while the upper transition is invariably an inversion but just below the upper inversion there is, in many cases, a region of decreasing temperatures with height, of about 2 gkm. in thickness, where the lapse rate is of the order of 3 to 6 °C/gkm. This type of structure can be explained as being due to a meridional movement of air in the neighbourhood of the tropopause, the upper transition corresponding to the tropopause of tropical latitudes and the lower one to that of temperate latitudes [4, 5]. In Poona also, tropopauses of this type are fairly frequent but the lower transition is less conspicuous and at a higher level than at Agra. Owing to the interposition of a layer of falling temperature with height, this type of transition would not be classified as one of type IV, but the physical nature is essentially the same. A full consideration of the question would involve the discussion of the variation of temperature with height at a few other stations also and is reserved for a separate paper. A summary of the analysis of Poona and Hyderabad data may, however, be included here.

Of 86 cases examined, 20 were of the non-composite type in which the stratosphere starts abruptly with an inversion and 66 of the composite type. In 40 of the latter there was no region of positive lapse-rate greater than 2°C/km. between the lower and upper transitions and in the remaining 26 such a region was present. To prevent confusion with the previous classification, we shall call these types *A*, *B* and *C*. The mean heights of tropopause of type *A* is 16·1 gkm. ; the mean upper height for types *B* and *C* 16·9 gkm. and the mean lower heights 14·7 and 14·4 respectively. The mean temperature of the tropopause is 192°·5 if we take the temperatures of *A* and those of the upper heights of *B* and *C*. If on the other hand, we take the temperatures of *A* and of the lower heights of *B* and *C*, the mean temperature is 198°. The corresponding mean heights are 16·6 and 14·9 gkm. In type *C*, the mean thickness of the region of positive lapse-rate is 1·3 gkm. and the mean lapse-rate 5°C/gkm. Representative height temperature curves of the three types are shown in *Fig. 3*.

Dividing the year into two parts, November to April and May to October, the relative distribution of the three types and the frequencies of different values of the lower and upper heights for all composite transitions are given in *Table 10*.

TABLE 10.—TYPES OF TROPOPAUSE AND FREQUENCIES OF LOWER AND UPPER HEIGHTS FOR COMPOSITE TRANSITIONS.

	No. of records with transition of type:			Frequencies of heights of											
				Lower transition.						Upper transition.					
	A	B	C	11·1 to 12.	12·1 to 13.	13·1 to 14.	14·1 to 15.	15·1 to 16.	16·1 to 17.	14·1 to 15.	15·1 to 16.	16·1 to 17.	17·1 to 18.	18·1 to 19.	19·1 to 20.
November—April.	6	22	21	1	4	12	16	10	..	..	10	14	15	2	2
May—October	14	18	5	..	..	4	5	12	2	1	2	13	6	1	..

5. Temperature-differences between Poona, Agra and Batavia.

Although the general nature of the variations of temperature with latitude at different heights is known, it is worth while examining in some detail the annual variation of the differences of temperature between Agra, Poona and Batavia as it brings out clearly the great influence of moisture and of radiation in continental and oceanic areas in altering the temperature of the atmosphere in the tropics. Differences of temperature between Poona (or Hyderabad) and Agra (*P-A*) and between Poona and Batavia (*P-B*) are given in *Table 11* (see also *Fig. 4*).

In the months November to April, Poona is warmer than Agra up to 11—13 gkm. and cooler above. The contrast of temperature is largest near the surface and at another height which lies in the neighbourhood of 8 gkm. There is an intermediate level which varies from 2 to 5 gkm. at which the temperature contrast is a minimum. This minimum appears to be due to a comparatively low temperature at Poona rather than to a high temperature at Agra and connected with the existence of a high pressure area over the Deccan, which causes the transport of air from north-west India after a clockwise circulation.

When we consider the difference of temperature between Poona and Batavia in the same months we see that, while in the lowest layer Poona temperatures are higher, they are in defect from 5 to 12 gkm. The former result is due to the difference in the times of ascent at Poona and Batavia and to the continentality of the climate of the Deccan during the larger part of the year. The height to which the higher temperatures near the surface extends at Poona is 3 gkm. in March and 4 gkm. in April; the defect of temperature at higher levels increases with the progress of the season from November to April. Near the top of the troposphere, Poona again gets to be higher in temperature. The level of least horizontal contrast of temperature lies in the neighbourhood of 12 gkm.

It will be noticed that near Poona in April, while a transport of air from either the north or south would cause a fall of temperature near the surface, the arrival of air from the north would be associated with lower temperatures at higher levels also, but air from

Table 11.—Mean Monthly Temperature Differences.

Height in gkm.	Poona (or Hyderabad) and Agra (*P-A*). Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Height in gkm.	Poona (or Hyderabad) and Batavia (*P-B*). Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	1	—9	6	..	—5	..	..	..	..	..	—10	..	**20**	..	..	..	..	..	..	..	..	..	..	..	..
19	—3	—12	—4	—12	—4	..	..	..	..	1	—9	—2	19	..	..	..	..	..	..	..	..	..	..	..	..
18	—3	—9	—7	—11	—3	—9	..	1	—3	3	—9	—1	18	..	..	..	..	..	..	8	..	..	..	7	..
17	—8	—6	—8	—8	—8	—5	..	2	1	3	—11	—4	17	7	12	5	7	..	5	6	7	5	—2	—3	11
16	—9	—4	—8	—7	—11	—4	..	1	—2	—1	—9	—8	16	2	10	4	5	4	1	1	3	—1	—4	—6	8
15	—6	—1	—6	—8	—11	—5	..	—3	—5	—4	—7	—8	**15**	0	8	1	3	2	2	3	4	—1	—4	—9	8
14	—6	—1	—5	—6	—8	—4	—4	—3	—3	—3	—2	—5	14	—3	7	—1	1	2	4	6	7	2	—3	—5	7
13	—3	1	—5	—5	—4	—3	—5	—4	—4	—3	1	1	13	—2	6	—2	—3	2	5	5	9	4	—2	—2	5
12	0	0	—4	—1	—2	—2	—7	—6	—4	—2	2	4	12	—1	4	—2	—3	—1	5	6	8	5	—1	—2	2
11	4	2	—1	1	—1	—3	—7	—6	—5	—1	3	7	11	—1	1	—3	—4	—3	5	7	8	4	—1	—2	1
10	8	4	1	3	—1	—3	—7	—7	—4	—1	4	8	**10**	—1	0	—3	—4	—4	3	7	7	4	—1	—2	1
9	6	8	2	5	1	—3	—6	—6	—4	0	5	7	9	—1	—1	—3	—3	—4	3	6	5	3	—1	—2	0
8	6	8	4	4	1	—3	—5	—6	—5	1	7	6	8	—1	—1	—3	—4	—4	3	5	4	2	0	—1	0
7	6	7	5	4	2	—2	—4	—5	—3	0	7	7	7	—2	—1	—1	—3	—3	2	5	3	2	0	—1	1
6	6	7	4	3	3	—1	—6	—4	—3	1	7	6	6	—2	—2	—1	—3	—1	2	3	3	3	0	—1	1
5	6	6	4	3	1	—1	—5	—4	—1	1	7	5	**5**	0	—2	0	—2	—1	2	3	3	3	1	0	1
4	6	6	1	3	—1	0	—4	—4	—1	1	7	3	4	0	—1	—2	—1	—1	3	3	1	2	1	0	1
3	5	9	2	3	—1	—1	—3	—4	—1	1	6	1	3	—1	0	0	2	2	3	2	1	2	0	0	—1
2·5	5	9	3	4	—3	—3	—3	—4	—1	0	5	1	2·5	—2	1	1	4	2	3	2	1	2	—1	—1	—2
2	6	9	5	3	—3	—4	—3	—3	—2	—1	5	2	2	—1	2	4	5	4	3	1	2	2	0	—1	—1
1·5	8	10	5	4	—4	—3	—2	—2	—2	—2	7	5	1·5	1	3	5	7	6	6	2	2	3	1	0	0
1	9	11	5	5	—3	—4	—1	—3	—1	—2	7	6	1	3	6	6	10	7	7	3	2	4	2	1	1

the south would bring higher temperature above. This feature becomes slightly altered in May when with increasing insolation over land Agra temperatures up to 5 gkm. get higher than those of Poona while Batavia temperatures remain lower and the differences get reversed at higher levels. The bearing of this on the structure of ' fronts ' formed in the Bay of Bengal during the pre-monsoon period has been discussed elsewhere[6, 7].

The months June to September form a class by themselves, Agra being warmer and Batavia colder than Hyderabad practically at all levels in the troposphere. These are the months, especially the last three, in which the monsoon depressions have an east to west travel across the north of the Peninsula. In June the mean temperature differences at 1 and 2 gkm. are similar to those in May, but from 3—5 gkm. the contrast of temperatures between Agra and Hyderabad is very small.* The extraordinarily small difference of temperature in October between the three places and the fact that *both* Agra and Batavia are colder than Hyderabad between 3 and 7 gkm. and warmer from 11 to 16 or 17 gkm. is noteworthy. This shows that in this month the thermal equator which lay over North India in August lies over the middle of the Indian Peninsula.

6. Some simultaneous ascents at Poona, Hyderabad and Agra.

It will be useful to collect here a few representative height temperature and height humidity diagrams for both Poona (or Hyderabad) and Agra on days when there were practically simultaneous ascents at both the places, together with notes on the general weather conditions prevailing on those days. Upper wind observations are also given whenever they are available. (See *Fig. 5.*)

18-1-30.

Agra was colder than Poona at all levels up to 13·7 gkm., with the maximum temperature difference, about 16°C, near the ground up to 1·5 gkm., the difference at other levels being about 5 to 11°C. Agra was slightly warmer than Poona between 13·7 and 16·4 gkm.

The conditions are representative of clear, anticyclonic weather in winter. Both Agra and Poona had got flooded with northwesterly or westerly air during the previous two or three days. On the morning of the 18th, the centre of the anticyclone was over Rajputana at 0·5 km. ; its position shifted southward with increase of height and at 3 km. there was a belt of high pressure at a latitude of about 15°N. The beginnings of the inversion at 1·4 gkm. at Agra and at 2·8 gkm. at Poona apparently mark the limit between the subsiding air above and the turbulent surface-heated air below. It will be seen from the diagram that the upper wind velocity at Poona increased rapidly from 5 m/s at 2·5 gkm. to 13 m/s at 3 gkm. and that at Agra it increased from 5 m/s at 1 gkm. to 9 m/s at 1·5 gkm. The air below the inversion was of slightly more northerly origin than air above. This is true of Poona also although the actual winds at 1·5 and 2 gkm. at Poona were from the south-west.

Attention may be drawn to the composite type of tropopause at Agra with inversions at 12·4 gkm. and 16·5 gkm. The tropopause at Poona also was composite although it was much less marked and the levels of the two transitions were only 1·4 gkm. apart.

The humidity curve also is characteristic of anticyclonic weather in the winter.

* The abnormally small difference of temperature between Hyderabad and Agra at 1 gkm. in July is apparently due to an abnormality in the Agra temperature.

17-7-31.

This was an occasion when the monsoon was giving widespread rainfall throughout the country except in Sind, Baluchistan and parts of Rajputana and the Punjab and in parts of the Madras Presidency. Agra had 0·4″ and Hyderabad 0·2″ of rainfall between 8 hrs. on the 17th and 8 hrs. on the 18th. On this day, data of soundings are available for Allahabad also in addition to those for Agra and Hyderabad. The temperature distributions at Agra and Allahabad are nearly identical, with the exception that there is a layer of feeble lapse-rate over Agra between 2·5 and 3 gkm. This inversion may be due to the interposition of comparatively dry north-west Indian air at Agra. It will be seen that there is also a sharp minimum of humidity at about 3 gkm. at Agra which is much less evident in the Allahabad curve. Both at Agra and Allahabad, the temperatures are higher than at Hyderabad by 3° to 8°, the largest differences being between 4 and 9 gkm. There is also an isothermal layer of about 0·7 gkm. thickness between 9 and 10 gkm. at Hyderabad, which probably marks the transition from the monsoon circulation to the easterly general circulation. In this connection, the sounding of 26th August 1929 which also shows the same feature may be compared. A height of 9 gkm. is, however, unusually large for the thickness of the monsoon.

26-8-29.

The temperature differences on this evening differ markedly from those on 17th July 1931. Agra was colder than Hyderabad from the surface to 2·2 gkm. and between 10 and 16 gkm. Between 2·2 and 10 gkm., the conditions were reversed.

On the morning of this day, a depression which was moving north-west from near the head of the Bay of Bengal was located at about 26°N and 77°E between Kotah and Jhansi. It had caused heavy rainfall to its south and south-west. From the few upper wind and cloud observations that are available, it appears that the air blowing over Agra on the evening of this day was coming from the Arabian Sea and had passed through the region of heavy rainfall to the south of the depression. The Peninsular portion of India had little rain recorded either on the morning of the 26th or the 27th, except a few falls west of the Ghats. The cloudiness there was also moderate and generally high or medium clouds were present. Owing to the scantiness of the observations, it is difficult to trace the trajectory of the air at either of the places to any considerable height. The low temperature of the air over Agra compared to Hyderabad at the surface and up to 2·5 gkm. is exceptional for the season and is no doubt an effect of the depression. Another unusual feature of the temperature distribution over Agra is the exceptionally low level of the tropopause (15·5 gkm.)—about 1 gkm. lower than that at Hyderabad. The weather and upper wind charts at 8 hrs. on the 26th are given in *Fig. 6*.

12-9-30.

On the morning of this day, a diffuse low pressure area characteristic of this month was extending from Gujarat to the north Madras coast. The centre of the low was near Kanker in the east Central Provinces. On the morning of the 13th, it had moved to between Khandwa and Pachmarhi in the west Central Provinces. Hyderabad recorded 0·4″ and 0·1″ of rainfall on the mornings of the 12th and 13th ; while Agra recorded no rainfall on either of the days. The winds over Agra up to about 6 km. were coming from the east from the north Bay of Bengal, while at Hyderabad in the first 2 km. the wind was

from the Arabian Sea. Agra temperatures were higher by 3° to 6° at all levels up to 20 gkm. the minimum difference—about 2°—being at 7 gkm. The westward movement of the depression stands in agreement with this distribution of temperature with higher temperatures to the north. At both places, there is a tendency for the humidity to fall off above 6 gkm.

Compared to the normal temperatures in this month, Agra temperatures are higher by about 2°C in the first 4 gkm. and Hyderabad temperatures lower by about the same amount up to 3 gkm. Agra's supply of air at these levels was on this day from rainy areas far out in the east instead of from the north as normally. The lower atmosphere of Hyderabad was cooled by rain in its immediate neighbourhood.

20-9-29.

The weather chart of this morning and of succeeding days showed very little gradient of pressure. On the evening of this day, rainfall accompanied by thunder occurred widespread over the extreme south of the Peninsula, in the north Bombay Deccan and in Gujarat. In north India, only Bihar, Kashmir and the Frontier Hills had scattered thundershowers.

Between 2 and 13 gkm. Agra temperatures are lower than those at Hyderabad. The monsoon conditions were gradually giving place to winter conditions in north-west India. As the wind-vectors show, the air over Hyderabad up to 8 km. was generally coming from the east or south, but the trajectory at 2 km. shows that air in the neighbourhood of this level might ultimately have been of northerly origin. The inversion at about 4·5 gkm. shown in the Agra sounding is a common feature of the upper air structure in this season and is associated with the sub-tropical high pressure ridge which is located over north-west India in this month.

15-10-31.

On this morning again, there was a depression lying over the east Central Provinces near Raipur. There had been widespread rainfall over the major portion of northern and Central India during the previous 24 hours.

On the morning of the 16th the depression had moved northward and was lying over the east United Provinces near Lucknow. Agra had skies overcast with clouds of the Stratus and Nimbus type and there was rain at intervals throughout the day.

The humidity diagram at Agra on the evening of the 15th shows that the air was practically saturated from 4·7 to 7 gkm. There is also a sharp decrease of lapse-rate at 4·7 gkm. From the upper wind charts it appears that easterly air from the north of the Bay was rising over rain-cooled air in the lower layers of the atmosphere.

At Hyderabad, there was no rain on the day in question and the winds were westerly up to about 3 km. At the time of ascent, the sky was partially clouded with alto-cumulus and alto-stratus. It is interesting to note that at Hyderabad the humidity decreased sharply at about 2·7 gkm. which also marked the beginning of a layer of smaller lapse-rate.

It may be noted that temperatures at Agra are lower than those at Hyderabad up to 6 gkm. and *vice versâ* at higher levels up to the stratosphere. The tropopause was lower at Hyderabad than over Agra.

7. Pressure.

Table 12 gives the monthly mean values of pressure at different heights. Curves of annual variation are shown in *Fig. 7*. The annual variation of pressure at all levels over

TABLE 12.—MEAN MONTHLY AND ANNUAL PRESSURES (MB.).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.	Range.
20	52	53	52	..	52	..	53	53	52	51	50	52	52	3
19	61	63	62	61	61	..	63	62	62	62	61	61	62	2
18	72	75	73	73	72	73	75	74	74	74	73	73	73	3
17	85	89	87	87	87	88	88	89	89	88	87	86	87	4
16	102	105	104	104	104	106	105	106	105	105	105	104	105	4
15	122	125	123	123	125	126	125	126	126	125	125	124	125	4
14	145	148	147	146	148	149	149	149	149	148	148	146	148	4
13	171	174	173	173	175	177	176	176	176	175	175	173	175	6
12	202	204	204	204	206	207	206	206	207	206	206	204	205	5
11	237	238	238	238	240	241	240	240	241	240	241	238	239	4
10	275	277	276	276	279	279	278	278	278	278	279	276	277	4
9	318	319	320	320	322	323	320	321	322	321	322	319	321	5
8	367	368	368	368	371	371	368	369	370	370	370	368	369	4
7	421	422	422	423	424	424	421	422	423	423	423	422	422	5
6	481	482	483	484	484	484	481	481	483	483	483	482	483	3
5	549	550	550	551	551	550	547	547	550	550	550	549	549	4
4	623	625	625	626	625	624	620	621	623	624	624	623	624	6
3	707	708	709	709	708	706	702	702	705	707	708	707	707	7
2·5	751	752	752	752	751	750	747	747	750	751	752	752	751	5
2	799	799	800	799	798	796	793	792	796	798	799	799	797	8
1·5	849	849	849	847	846	844	842	841	846	847	849	848	846	8
1	900	899	899	898	897	895	893	891	896	899	900	900	897	9
Surface (0·54)	950	948	948	946	944	943	943	942	946	948	949	950	946	8
NORMAL (at 8 A.M.) AT POONA.	955	954	952	951	949	945	945	947	949	952	954	955	951	10
NORMAL (at 8 A.M.) AT HYDERABAD.	957	955	954	951	949	947	946	948	950	953	956	957	952	11

the Deccan is considerably smaller than that over North India. From the surface to 2 gkm. there is a well-marked pressure-minimum at the time of the monsoon in August and a flat maximum in November-March. The occurrence of the minimum in August instead of in June or July is due to abnormally low pressures on the days of sounding balloon ascents. With increase of height, the monsoon pressure-minimum gets less and less marked and at 10 gkm. has given place to a flat maximum which prevails during the months May to November. The difference between the maximum and minimum values of monthly mean pressures is least at 6 gkm. but the value remains small at all higher levels.

8. Monthly mean pressure-differences between Poona and Agra and Poona and Batavia.

In the discussion of Agra sounding balloon results, the mean monthly pressures over Agra, Batavia and Europe were compared. It is now possible to split up the pressure-differences between Batavia and Agra into two parts: Batavia *minus* Poona and Poona *minus* Agra. The mean monthly diffrences of pressure at dynamic kilometres are contained in *Table 13* and are shown graphically in *Fig. 8*.

In the interpretation of the pressure-differences between Batavia and Poona (or Hyderabad) it has to be remembered that the two places lie on opposite sides of the equa-

tor. But as Batavia is only 6° south of the equator, while Poona is 18½° north, and as pressure gradients are generally weak in the neighbourhood of the equator it may generally be assumed that Batavia pressures represent pressures at the equator.

At 1 gkm., the pressure-difference *B—P* is a maximum in August and minimum in winter. During the monsoon (July-August), the pressure-difference gradually decreases to zero at 8 gkm. and reverses sign higher up. The easterly upper winds increase in strength up to the tropopause where they seem to reach the maximum velocity. It is known from pilot balloon winds at Bangalore[8] and Hyderabad in July and August (see *Fig. 12*) that the westerly winds of the monsoon change to easterly at 5—7 km. On days when pilot balloon observations are not possible owing to the activity of the monsoon, the westerly winds may even extend higher. In the winter and hot season, there are negative pressure differences at 2 and 3 gkm. which account for the weak anti-cyclonic winds prevailing at these levels in these months in the middle and south of the Peninsula. In the first four months of the year, the mean gradient for westerly winds increases in strength above 4 gkm. and shows a maximum at 9—11 gkm. (Pressure values for May at Batavia are abnormally high.) The fact that the pressure-differences in the higher parts of the troposphere are larger in March-April than in November-December suggests that easterly upper winds are more common in the latter months than in the former. The positive differenes *B—P* in October are not consistent with the available upper wind observations. At Bangalore, the upper winds begin to have an appreciable easterly component at about 5 km., at Hyderabad at 10 km. and at Poona at 12—13 km. The winds at lower levels are generally weak. The transitional character of the weather of the month and the smallness of the number of observations may be responsible for the disagreement.

In the first few kilometres of the stratosphere, the wind appears to be easterly in all parts of the year.

Considering the pressure-differences between Poona and Agra, the following points are noteworthy :—

(1) During the winter, the gradient is for westerly winds up to 20 gkm. It increases rapidly in strength with increasing height above surface, reaches a maximum at 8—10 gkm. and decreases again at higher levels. Owing to the decrease of density with height, the maximum wind velocity will be in the neighbourhood of 12 gkm.

(2) In March and April, besides a general decrease in the gradient at all levels, there is a comparative maximum at 2—3 gkm. This arises from the fact that there is a high pressure area at these levels over the Deccan.

(3) In May, the gradient becomes very small at 4 gkm. and a gradient for easterly winds sets in above 14 gkm.

(4) The gradient for easterly winds descends to 9 gkm. in June and to 4·5 gkm. in July, August and September. The maximum gradient for easterly winds during the monsoon occurs near 12 gkm. The exceptionally small difference of pressure in the first 4 gkm. in August is, as has already been said, due to the abnormally low pressures in Hyderabad on the days of the sounding balloon ascents.

(5) The pressure-difference is small at all levels in October, but the mean gradient is for easterly winds above 13 gkm. and for westerly winds below.

Table 13.—Mean Monthly Pressure Differences (mb.).

(a) Poona (or Hyderabad) and Agra (*P-A*).

Height (gkm.).	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	1	2	0	..	—1	..	..	..	..	..	—2	..
19	1	2	0	—2	—3	..	..	..	—1	—1	0	0
18	1	3	0	0	—3	—3	..	—2	—1	0	1	0
17	1	3	0	0	—2	—2	..	—2	—1	—1	2	—1
16	2	4	1	1	—2	—2	..	—2	—2	—1	4	2
15	4	5	0	1	0	—2	..	—3	—2	—1	5	3
14	5	6	2	2	—1	—2	—2	—3	—3	—2	5	3
13	5	7	2	3	0	—1	—4	—4	—3	0	6	6
12	7	8	3	4	1	—2	—5	—5	—2	0	7	7
11	9	9	4	5	1	—1	—4	—4	—3	1	9	7
10	10	12	5	5	2	—1	—5	—4	—3	1	9	7
9	7	9	5	5	0	0	—4	—4	—2	0	9	5
8	8	11	5	5	2	1	—3	—3	—2	1	9	5
7	6	10	5	5	1	1	—2	—2	—2	1	9	5
6	7	11	4	6	1	2	—1	—2	—1	1	8	3
5	6	10	4	5	1	1	—1	—2	0	1	7	2
4	6	11	4	5	0	3	1	0	1	1	6	2
3	5	8	5	6	1	3	2	0	1	1	6	2
2	5	8	4	4	2	5	4	0	2	0	4	2
1	1	3	1	3	2	5	4	0	2	0	1	—1

(b) Batavia and Poona (*B-P*).

Height (gkm.).	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	—4	—4	—2	..	—2	..	—4	—3	—2	0	1	—4
19	—2	—4	—2	—1	0	..	—4	—2	—1	0	0	—3
18	—1	—4	—1	—1	1	—1	—4	—2	—1	0	0	—3
17	1	—3	0	0	1	—2	—3	—4	—2	0	1	—2
16	1	—1	1	0	2	—3	—3	—4	—1	1	1	—2
15	1	—1	2	2	1	—3	—3	—4	—2	1	1	—2
14	2	0	2	3	2	—2	—3	—4	—2	2	2	—1
13	3	1	3	3	3	—2	—3	—3	—2	2	2	0
12	2	2	2	3	3	—2	—3	—3	—3	0	2	0
11	2	2	3	3	4	—1	—3	—2	—2	1	1	0
10	2	2	3	4	3	—1	—1	—1	0	2	2	1
9	3	3	2	3	3	—1	0	0	—1	1	2	1
8	2	2	2	2	1	—1	0	0	—1	0	1	0
7	2	2	2	1	1	0	1	1	0	1	1	0
6	2	2	1	0	2	0	2	2	0	2	2	1
5	2	2	1	0	2	2	3	4	1	2	2	1
4	1	0	0	—1	1	1	4	3	1	1	1	1
3	0	—1	—2	—2	0	1	5	5	2	0	—1	—1
2	—1	—1	—2	—1	0	2	5	6	2	0	—1	—1
1	0	1	1	2	3	5	7	9	5	2	0	0

9. Places of fall of sounding balloons.

The distances and directions of the places of fall of sounding balloons together with the maximum height reached by each ascent are given in *Table 14*. The places of fall for ascents from Poona and Hyderabad are also plotted in *Figs. 9 (a)* and *9 (b)*; the former

TABLE 14.—DISTANCES AND DIRECTIONS OF PLACES OF FALL OF SOUNDING BALLOONS, WITH GREATEST HEIGHTS REACHED BY THEM.

Serial No.	Date of ascent.	Distance (km.).	Direction (Degrees from N.).	Greatest height (gkm.).	Serial No.	Date of ascent.	Distance (km.).	Direction (Degrees from N).	Greatest height (gkm.).
				(a) Balloons sent up from Poona.					
1	28th Oct. 1928	33	60	18·7	33	2nd May 1930	5	95	18·6
2	10th Nov. 1928	83	85	14·1	34	8th May 1930	107	220	15·9
3	13th Nov. 1928	79	50	12·0	35	13th May 1930	27	210	18·0
4	15th Nov. 1928	61	55	10·3	36	14th May 1930	29	131	20·6
5	23rd Nov. 1928	170	100	16·3	37	15th May 1930	29	131	23·5
6	4th Dec. 1928	174	81	11·7	38	21st May 1930	66	57	18·7
7	28th Dec. 1928	114	90	18·6	39	30th Oct. 1930	68	349	12·2
8	15th Jan. 1929	104	155	11·6	40	5th Nov. 1930	94	83	21·1
9	2nd Feb. 1929	211	103	20·2	41	26th Nov. 1930	74	120	25·6
10	22nd Feb. 1929	111	135	25·9	42	29th Nov. 1930	66	57	18·5
11	7th Mar. 1929	3	90	19·5	43	5th Dec. 1930	106	30	15·5
12	7th April 1929	80	49	15·9	44	19th Dec. 1930	114	56	21·5
13	8th July 1929	81	262	11·8	45	9th Jan. 1931	283	177	17·9
14	10th Dec. 1929	88	80	18·1	46	12th Jan. 1931	176	79	19·3
15	19th Dec. 1929	109	55	23·5	47	7th Feb. 1931	332	80	19·2
16	21st Dec. 1929	117	87	18·9	48	12th Feb. 1931	274	124	20·8
17	30th Dec. 1929	117	87	18·9	49	13th Feb. 1931	274	124	19·1
18	7th Jan. 1930	117	87	21·2	50	17th Feb. 1931	332	80	20·2
19	10th Jan. 1930	139	89	20·0	51	18th Feb. 1931	258	74	18·7
20	14th Jan. 1930	228	87	16·8	52	22nd Feb. 1931	236	59	20·1
21	15th Jan. 1930	242	103	17·0	53	23rd Feb. 1931	258	74	18·7
22	16th Jan. 1930	122	89	19·5	54	24th Feb. 1931	293	72	19·3
23	17th Jan. 1930	138	95	16·8	55	25th Feb. 1931	343	77	18·9
24	18th Jan. 1930	138	95	20·2	56	11th Mar. 1931	236	99	18·8
25	31st Jan. 1930	207	75	14·5	57	16th Mar. 1931	161	44	16·7
26	3rd Feb. 1930	169	99	21·9	58	27th Mar. 1931	172	58	24·7
27	23rd Feb. 1930	228	99	17·4	59	17th April 1931	114	56	19·9
28	9th Mar. 1930	31	153	17·9	60	1st May 1931	93	83	20·3
29	12th Mar. 1930	65	57	16·4	61	1st Oct. 1931	129	270	17·6
30	8th April 1930	207	75	17·0	62	2nd Dec. 1931	290	117	14·5
31	18th April 1930	114	56	23·7	63	3rd Dec. 1931	161	120	28·1
32	20th April 1930	131	61	18·0	64	16th Dec. 1931	174	130	21·2
				(b) Balloons sent up from Hyderabad.					
1	16th Aug. 1929	170	265	18·5	20	4th Oct. 1930	13	292	17·4
2	17th Aug. 1929	232	271	15·7	21	7th Oct. 1930	93	272	19·1
3	26th Aug. 1929	57	258	17·8	22	11th Oct. 1930	93	272	19·6
4	4th Sept. 1929	136	265	16·5	23	14th Oct. 1930	1	135	15·7
5	14th Sept. 1929	287	263	16·1	24	9th July 1931	185	273	17·1
6	17th Oct. 1929	24	280	17·6	25	25th July 1931	112	271	15·7
7	6th June 1930	112	271	18·4	26	1st Aug. 1931	200	275	21·0
8	10th June 1930	267	284	17·1	27	8th Aug. 1931	112	271	19·8
9	18th June 1930	112	271	16·9	28	17th Aug. 1931	161	275	21·8
10	8th July 1930	101	255	20·4	29	22nd Aug. 1931	145	256	21·8
11	12th July 1930	70	244	16·9	30	6th Sept. 1931	578	278	17·0
12	19th July 1930	186	253	18·5	31	10th Sept. 1931	222	284	16·9
13	26th July 1930	77	251	17·0	32	13th Sept. 1931	414	275	17·6
14	17th Aug. 1930	112	271	20·5	33	18th Sept. 1931	339	273	16·8
15	19th Aug. 1930	112	271	25·9	34	29th Sept. 1931	563	255	17·4
16	6th Sept. 1930	112	271	17·6	35	13th Oct. 1931	176	251	17·1
17	12th Sept. 1930	156	251	20·4	36	15th Oct. 1931	112	271	18·3
18	24th Sept. 1930	36	280	17·5	37	18th Oct. 1931	56	315	18·9
19	29th Sept. 1930	70	244	14·9	38	24th Oct. 1931	19	43	21·0

are further sub-divided according to season. It will be seen that of the balloons sent up from Poona, those released in November to February fell invariably towards the east; the longest distances travelled being generally in February; those sent up in March to May also fell towards the east but on the average nearer than in the previous season.

All the balloons sent up from Hyderabad in June to October fell towards the west, those in October falling nearest the place of release. Of the balloons sent up from Poona or Hyderabad, the longest distance travelled was by one sent up from Hyderabad on 6th September 1931 which rose to 17 gkm. and fell 578 km. to the west. The shortest distance travelled was also by a balloon from Hyderabad on 14th October 1930 which fell within a mile of the observatory after reaching a height of about 16 gkm.

10. Density.

Mean monthly values of density are given in *Table 15*. The values have been corrected for humidity.

TABLE 15.—MEAN MONTHLY AND ANNUAL DENSITIES (GMS. PER CUBIC METRE).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Mean.	Range.
20	84	89	88	..	88	..	90	89	89	87	88	86	88	6
19	103	109	108	109	106	..	109	106	107	104	107	103	106	6
18	126	131	130	131	130	131	133	128	127	129	130	127	129	7
17	152	156	157	155	158	158	157	158	158	157	157	153	156	6
16	181	183	185	185	188	189	188	187	188	188	189	185	186	8
15	214	214	215	216	222	220	220	219	221	220	221	217	220	8
14	252	247	250	249	253	252	252	250	251	252	253	248	251	6
13	285	281	284	288	285	286	285	284	285	286	287	284	285	7
12	323	319	323	325	324	322	323	322	324	325	325	323	323	6
11	362	360	364	365	363	361	361	360	362	363	365	363	362	5
10	408	405	409	409	409	406	403	404	403	406	408	408	407	6
9	456	455	459	458	456	453	450	452	454	454	456	458	455	9
8	511	509	511	511	509	506	502	504	506	508	508	510	508	9
7	570	571	570	572	567	565	561	562	562	569	567	568	567	11
6	637	638	636	641	630	629	628	626	629	633	633	635	633	12
5	709	710	706	710	703	697	697	695	699	703	703	704	703	15
4	787	789	792	787	781	773	772	777	776	779	781	783	781	20
3	875	871	875	863	858	855	857	861	861	867	869	875	867	20
2·5	922	913	912	901	901	898	904	906	907	911	917	922	909	24
2	969	957	954	941	939	944	949	949	953	959	965	968	954	30
1·5	1012	1001	997	985	983	983	995	995	999	1003	1009	1013	998	30
1	1054	1042	1041	1025	1025	1026	1043	1042	1042	1049	1045	1048	1040	29
Surface	1093	1083	1079	1068	1066	1072	1084	1079	1091	1093	1093	1104	1086	38

11. Humidity.

Mean monthly values of relative humidity up to 12 gkm. are given in *Table 16*. Although it is known that the indications of the hair hygrometer cannot be relied on at temperatures below about 255° A (heights above 8 gkm.) it is found from records that there are often significant changes occurring even above this level. The mean values above 8 gkm. may have a qualitative significance. The maximum humidity during the year occurs in August from the surface to 7 gkm. Between 8 and 12 gkm. the maximum occurs

in July, but at these levels, the humidity is large and nearly the same in all the months June-September. The minimum occurs at all levels in January. A secondary maximum in February and a corresponding minimum in March are also noticeable. It is probable that like February temperatures, the February humidities are also abnormal.

TABLE 16.—MEAN MONTHLY RELATIVE HUMIDITIES.

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
12	5	29	17	44	37	53	66	56	60	25	18	16
11	11	28	18	45	36	53	70	59	62	24	17	17
10	13	28	18	45	39	56	75	59	63	26	30	20
9	13	29	18	45	44	66	79	60	69	26	29	21
8	12	27	18	51	47	69	75	72	70	31	27	21
7	11	27	17	55	48	70	74	84	64	36	29	22
6	11	30	16	61	53	66	72	89	66	41	40	25
5	12	33	28	61	65	71	80	86	74	51	41	27
4	14	37	36	77	71	74	77	92	85	65	39	37
3	26	49	32	72	65	78	78	93	80	73	46	47
2·5	35	46	29	58	64	77	78	92	76	73	65	59
2	37	40	25	49	62	76	86	88	80	74	72	63
1·5	36	36	22	43	59	67	82	87	79	74	67	63
1	37	33	22	39	54	63	79	83	76	68	60	55
Surface .	40	40	31	37	43	56	75	73	79	69	51	57

In all months (except January), humidity rises from the surface, reaches a maximum at a level varying from 1·5 to 4 gkm., and falls off more or less rapidly. The level of maximum is higher in April and May than in either the monsoon or winter months. In September, when the monsoon is weak and there are breaks in the rains, there are two maxima at 2 and 4 gkm., with an intervening minimum at 2·5 gkm. In the winter months, the fall of humidity above the maximum is most rapid, and the values above are quite small; whereas, in the monsoon, the fall is gradual and relative humidities are high upto 8 gkm. In about half the number of the winter ascents, the humidity is less than 15 per cent. above 3 or 4 gkm. The monthly means of vapour pressure and of mixing ratio are given in *Tables 17 and 18* respectively.

TABLE 17.—MEAN MONTHLY VALUES OF VAPOUR PRESSURE (MB.).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10	..	0·1	..	0·1	0·1	0·1	0·2	0·2	0·2	0·1	0·1	..
9	0·1	0·1	0·1	0·2	0·2	0·4	0·5	0·3	0·4	0·1	0·1	0·1
8	0·1	0·2	0·1	0·4	0·5	0·9	0·9	0·9	0·8	0·3	0·3	0·2
7	0·1	0·5	0·3	0·9	1·0	1·6	1·7	1·8	1·5	0·7	0·6	0·4
6	0·3	0·8	0·5	1·7	2·0	2·5	2·5	3·3	2·4	1·4	1·4	0·5
5	0·5	1·5	1·4	2·8	3·7	4·5	4·7	5·3	4·3	2·9	2·3	1·4
4	1·1	2·7	2·5	5·8	6·2	7·1	6·7	7·5	7·4	5·7	3·3	2·9
3	2·8	5·6	3·5	9·5	9·4	11·7	9·3	11·1	10·1	8·7	5·7	4·9
2·5	4·2	6·7	4·5	10·5	11·6	14·0	11·7	12·9	11·8	10·6	8·8	7·0
2	5·6	7·8	5·3	12·0	15·0	16·2	15·6	16·0	14·6	12·6	11·5	9·4
1·5	7·4	9·2	6·2	13·6	17·6	19·4	18·6	19·1	17·9	16·3	14·3	12·2
1	10·4	11·1	7·6	16·6	21·6	24·4	21·5	22·0	22·0	19·1	15·9	14·7
Surface .	14·7	17·0	14·3	18·6	21·6	24·5	26·0	27·7	27·4	23·2	18·1	17·5

TABLE 18.—MEAN MONTHLY VALUES OF MIXING RATIO (GMS. OF WATERVAPOUR PER KGM. OF DRY AIR).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10	..	0·2	..	0·2	0·2	0·2	0·4	0·4	0·4	0·2	0·2	..
9	0·2	0·2	0·2	0·4	0·4	0·8	1·0	0·6	0·8	0·2	0·2	0·2
8	0·2	0·3	0·2	0·7	0·8	1·5	1·5	1·5	1·4	0·5	0·5	0·3
7	0·1	0·7	0·4	1·3	1·5	2·4	2·5	2·7	2·2	1·0	0·9	0·6
6	0·4	1·0	0·6	2·2	2·6	3·2	3·2	4·3	3·1	1·8	1·8	0·6
5	0·6	1·7	1·6	3·2	4·2	5·1	5·3	6·0	4·9	3·3	2·6	1·6
4	1·1	2·7	2·5	5·8	6·2	7·1	6·7	7·5	7·4	5·7	3·3	2·9
3	2·5	4·9	3·1	8·5	8·4	10·5	8·3	10·0	9·0	7·8	5·0	4·4
2·5	3·5	5·6	3·7	8·8	9·8	11·8	9·9	11·0	9·9	8·9	7·4	5·9
2	4·4	6·4	4·2	9·5	12·0	13·0	12·4	12·8	11·6	10·0	9·1	7·4
1·5	5·5	6·8	4·6	10·1	13·3	14·7	14·1	14·4	13·4	12·2	10·6	9·1
1	7·3	7·8	5·3	11·7	15·4	17·4	15·4	15·8	15·7	13·5	11·2	10·3
Surface .	9·7	11·4	9·5	12·2	14·6	16·6	17·7	18·9	18·6	15·6	12·1	11·7

A few characteristic height-humidity curves with the corresponding height-temperature and upper wind diagrams are given in *Fig. 10.* Notes of weather conditions during the days are given below :—

7-4-29.

This was an occasion when a hot weather thunderstorm was in progress in the neighbourhood of Poona. At the time of ascent, there were CuN and mammato-cumulus clouds present and rain was just beginning to fall. On the morning of the 7th, a diffuse low pressure area was lying over the Konkan and the Bombay Deccan with a more extensive one over the east United Provinces and Bihar. The upper winds in the morning were south-south-easterly at 4 and 5 km. and ACu clouds were coming from the south. The balloon fell 80 km. to the north-east of Poona after reaching a height of 15·9 gkm. The rain measured at 8 hours on the 8th was 0·5″.

Note the dryness and high lapse-rate of the surface air and the high humidity of air above 2·7 gkm.

12-7-30.

The monsoon was weak in the Peninsula and there were only scattered light falls of rain there. At Hyderabad itself at the time of ascent, there were a few cumulus clouds which gradually cleared by 20 hours. Although there was high humidity at certain levels, the lapse-rates were small between 4 and 6·5 gkm.

29-7-29.

This is the record of an ascent made at Poona. The dry layer of air between 2 and 6 gkm. is exceptionally deep for the season. A depression which was lying over lower Sind on the morning of the 28th had moved off westwards on the 29th morning and become unimportant. The dry air had apparently come from the western side of the depression from Persia and Iraq. The increase of humidity above 6 gkm. indicates the beginning of easterly upper winds.

22-8-31.

On this day, a depression was lying over the Central Provinces and was causing heavy rain to its south-west. Winds at Hyderabad were westerly to south westerly up

to at least the middle cloud level. The humidity pen was apparently displaced, but there is no doubt that the humidity was very high between 3 and 6·7 gkm.

13-9-31.

On the morning of this day, a diffuse low pressure area characteristic of the month was lying over the west Bay of Bengal off the north Madras Coast. Widespread thundershowers occurred in the south of the Peninsula, Mysore and the Deccan on the 13th ; Hyderabad recorded 0·3″ on the 14th morning. The sudden fall of humidity above 4·7 gkm. and the large moisture content of the lower layers are significant.

1-10-31.

On this day, there were ascents both at Poona and at Hyderabad. A practically stationary low pressure area was lying over north Hyderabad, causing widespread rain from the Konkan to the Central Provinces. The humidity curves at both the places were somewhat similar in that it was nearly saturated at the surface with a slow fall of humidity, up to 4·5 gkm. at Poona and 4·7 gkm. at Hyderabad and a more rapid fall above. This type of humidity distribution is rare and represents the condition of stable rain-cooled air.

11-10-30.

This represents conditions prior to setting in of the north-east monsoon. Surface pressure gradients were weak and rainfall was practically confined to the Peninsula south of latitude 20° mostly attended with thunder. North India had become overspread with continental air from the north-west. As the wind-vectors show, easterly air was bringing in moisture up to about 6 km.

12. Potential temperatures and tephigrams.

The following tables (*Tables 19* and *20*) give the monthly mean potential temperatures at different levels above Poona (or Hyderabad) and the mean differences of potential temperature between Poona and Agra (*P—A*) and between Poona and Batavia (*P—B*). The seasonal variation of potential temperature at Poona (or Hyderabad) is also represented diagrammatically in *Fig. 11*. In *Fig. 12* are drawn the mean monthly tephigrams and pressure-dew-point diagrams. For comparison, the tephigrams of Agra also are drawn. The full lines represent the tephigrams for Poona or Hyderabad and the broken lines those for Agra. The lines with alternate dashes and dots represent the dew-point-pressure diagrams for Poona or Hyderabad. Along a line inclined at 45° to the temperature axis, the N. and E. components of wind at Poona or Hyderabad have also been indicated in the form of " clothes-line " diagrams. These winds are based on all available pilot balloon results up to the end of 1931 and do not relate to the days of the sounding balloon ascents only. The diagrams form a convenient summary of information about upper air conditions. Most of the points that call for comment have been touched on in other connections. One interesting feature of the monsoon tephigrams may, however, be pointed out. The atmosphere over the Deccan in the region of the upper easterly winds is definitely more stable than in the corresponding region over Agra whose tephigram closely follows the saturation adiabatic. This feature and the large wind-velocities at 2 and 3 km. leading to a dynamical suction effect at higher levels are

responsible for the comparative absence of thunderstorms in the Deccan during the time when the monsoon low lies over the Gangetic valley. A large rate of shear of wind above the layer of maximum humidity would make the cumulus clouds extend horizontally and prevent individual clouds growing upwards and producing the large differences of potential necessary for thunder.

TABLE 19.—MEAN MONTHLY AND ANNUAL POTENTIAL TEMPERATURES (°A, STANDARD PRESSURE BEING 1,000 MB.).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual.	Range.
20	499	479	477		477		475	465	475	480	467	488	478	34
19	57	45	39	431	43		41	51	44	57	36	50	45	21
18	25	19	13	09	11	407	14	25	14	23	13	23	16	18
17	397	399	389	393	385	388	392	394	392	391	389	397	392	14
16	76	85	76	75	67	71	70	75	72	72	70	74	74	18
15	63	72	64	63	57	60	61	64	61	61	60	64	63	15
14	51	63	57	57	57	58	58	59	57	56	55	57	57	12
13	48	58	52	49	53	56	55	57	55	53	52	52	53	10
12	46	53	48	46	50	54	53	53	52	50	50	49	50	8
11	43	48	45	43	47	51	50	50	49	48	47	45	47	8
10	41	45	41	41	44	47	48	47	47	45	45	42	44	7
9	38	40	38	39	42	44	44	43	44	42	42	38	41	6
8	34	35	35	34	38	40	41	40	39	38	39	35	37	7
7	29	31	32	30	34	35	36	35	35	33	34	32	33	7
6	25	25	26	25	29	30	29	30	30	31	29	27	28	6
5	21	20	21	20	23	25	25	25	24	23	24	22	23	5
4	16	15	14	16	18	20	19	19	19	18	19	17	17	6
3	10	11	11	14	15	16	14	13	13	12	13	09	13	7
2·5	07	10	10	14	14	13	11	10	11	10	09	·07	11	7
2	06	09	11	13	13	11	09	09	09	08	07	05	09	8
1·5	05	09	10	12	12	11	07	07	07	06	05	04	08	8
1	05	08	09	13	11	10	06	05	05	05	04	03	07	10
Surface	05	07	09	11	09	08	05	06	04	04	04	02	06	9

The tephigrams of the transition months May and October are also of particular interest as bringing out the essential difference of continental and maritime air in tropical regions. It will be seen that in both these months, while in the lower layers up to 3 or 4 gkm. the Agra tephigram lies above that of Poona, in the middle troposphere, their relative positions are interchanged. Above 8 to 10 gkm. the Agra tephigram again lies higher.

The supplementary *Tables 21—26*, in the Appendix, give :—

(*a*) the number of meteorographs sent up in each month from Poona and Hyderabad and the number recovered out of these,

(*b*) the mean monthly values of pressure, temperature and density at *geometric* kilometres, and

(*c*) the mean monthly values of heights and temperatures corresponding to principal pressure values.

The instrumental equipment required for the present work was almost entirely supplied by the Upper Air Observatory, Agra, and the sounding balloon work carried out from Poona and Hyderabad owes much of its success to the interest taken in it by Mr. G. Chatterjee, Meteorologist-in-charge of the Agra Observatory. The thanks of the Department are due to the Government of His Exalted Highness the Nizam of Hyderabad and to Mr. T. P. Bhaskar Sastri, Director of the Nizamiah Observatory, for permission and facilities for carrying on sounding balloon work from Hyderabad. Many other mem-

TABLE 20.—MEAN MONTHLY POTENTIAL TEMPERATURE DIFFERENCES.

(a) Poona (or Hyderabad) and Agra (P-A).

Height in gkm.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.
17	—18	—18	—16	—18	—15	—7		5	2	6	—24	—7
16	—21	—12	—13	—14	—19	—5		6	—3	1	—20	—17
15	—14	—7	—12	—15	—20	—9		0	—6	—5	—15	—18
14	—14	—6	—10	—11	—12	—5	—3	—3	—5	—4	—6	—13
13	—9	—3	—9	—9	—7	—4	—6	—3	—4	—5	—2	—2
12	—3	—3	—8	—3	—3	—2	—8	—6	—4	—4	0	3
11	2	—3	—3	—2	—3	—3	—10	—7	—7	—3	0	7
10	7	2	—1	2	—2	—4	—9	—8	—5	—2	4	8
9	6	7	2	5	2	—4	—7	—8	—5	1	4	8
8	6	6	5	4	1	—4	—6	—7	—6	1	8	7
7	5	7	6	4	3	—2	—5	—6	—4	1	8	8
6	6	6	5	3	2	—1	—7	—5	—3	3	8	6
5	6	6	3	1	1	—1	—6	—4	—1	0	7	5
4	6	5	0	2	—1	—1	—6	—4	—1	0	8	3
3	4	8	2	3	—2	—2	—4	—4	—2	0	7	0
2	6	9	5	4	—4	—5	—3	—3	—2	—1	6	2
1	10	11	5	5	—4	—5	0	—3	—3	—2	7	6

(b) Poona (or Hyderabad) and Batavia (P-B).

Height in gkm.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.
17	21	24	9	16		10	11	14	11	—1	1	25
16	9	21	15	14	12	5	2	6	0	—3	—7	17
15	7	18	7	11	8	3	7	9	—1	—2	—11	16
14	0	15	2	8	11	8	12	10	3	—1	—4	14
13	2	15	1	1	6	9	10	15	8	0	0	11
12	3	10	1	0	2	10	12	15	9	1	0	6
11	1	4	0	—2	—1	9	11	13	8	4	0	3
10	0	2	—2	—3	—3	6	12	11	7	1	—1	2
9	2	2	—1	—2	—2	6	9	8	5	1	0	2
8	1	0	—1	—3	—2	6	9	7	4	3	1	2
7	—1	0	0	—3	—1	4	7	5	4	1	1	2
6	0	—1	0	—2	0	4	5	5	5	4	1	2
5	1	—1	0	—3	0	4	5	5	4	2	2	2
4	0	—2	—3	—1	0	3	4	3	3	1	2	1
3	—1	0	0	2	3	4	3	2	3	1	1	—1
2	0	2	5	5	5	4	3	3	3	1	0	—1
1	3	6	6	11	7	8	4	3	3	1	0	1

bers of the staff of the Upper Air Section at Poona have participated in the calibration of the instruments and the working out of the records, to all of whom the authors' thanks are due.

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APPENDIX.

Supplementary Tables.

TABLE 21.—NUMBER OF BALLOONS SENT UP (n_1) AND NUMBER RECOVERED (n_2).

Year.	Jan.		Feb.		Mar.		Apl.		May.		June.		July.		Aug.		Sep.		Oct.		Nov.		Dec.		Whole Year.	
	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2
Poona.																										
1928																			3	1	8	5	4	3	15	9
1929	5	4	4	2	5	3	7	2	6	3	4	1	5	2							3	3	11	7	50	27
1930	12	8	4	2	7	2	7	3	11	5			4	2	6	2	5	3	5	4	5	3	14	3	80	37
1931	8	7	16	11	7	4	4	2	7	2	4	0	9	3	2	0	2	0	5	0			14	7	78	36
TOTAL	25	19	24	15	19	9	18	7	24	10	8	1	18	7	8	2	7	3	13	5	16	11	43	20	223	109
Hyderabad.																										
1929															7	4	10	8	9	5	2	2			28	19
1930											9	5	8	6	8	5	20	12	10	5	2	0			57	33
1931											9	2	12	7	15	8	11	6	11	9	4	3			62	35
TOTAL											18	7	20	13	30	17	41	26	30	19	8	5			147	87

TABLE 22.—MEAN MONTHLY TEMPERATURES (°A) AT **Geometric** KILOMETRES.

Heights in km.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	10	04	02		02		03	06	02	05	97	08
19	03	00	97	94	97		98	03	99	04	96	03
18	98	99	94	94	93	93	95	00	96	98	94	99
17	95	00	93	95	91	93	94	96	95	94	92	95
16	96	02	96	96	93	95	95	97	95	95	94	96
15	99	06	01	00	99	01	01	02	01	00	99	01
14	03	11	07	06	07	09	10	10	09	07	07	07
13	11	18	14	12	16	18	17	18	17	16	15	14
12	20	25	22	21	24	26	25	26	25	24	23	22
11	28	32	29	29	32	34	34	34	33	32	32	30
10	37	39	37	37	40	41	42	41	41	40	40	37
9	44	46	44	45	48	49	49	49	49	47	48	44
8	51	52	52	51	55	56	56	56	56	55	55	52
7	57	59	59	59	61	62	62	62	62	60	61	60
6	64	64	65	64	68	68	67	68	68	67	67	65
5	70	70	71	70	73	74	73	73	73	73	73	71
4	76	76	75	77	79	80	79	77	79	78	78	77
3	81	83	82	85	86	86	84	83	84	83	83	81
2	87	90	92	94	94	92	89	89	89	89	87	86
1	96	99	00	03	02	01	96	95	97	96	95	94

N.B.—The hundreds figure has been omitted throughout the table.

TABLE 23.—MEAN MONTHLY PRESSURES (MB.) AT **Geometric** KILOMETRES.

Height in km.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	56	57	56		56		58	58	57		54	56
19	66	68	67	66	66		68	67	67	67	66	66
18	77	80	78	78	77	78	80	79	79	79	78	78
17	91	95	93	93	93	94	94	95	95	94	94	92
16	109	112	111	111	111	113	112	113	112	112	112	111
15	130	133	131	131	133	134	133	134	134	133	133	132
14	153	156	155	154	156	157	157	157	157	156	156	154
13	180	183	182	182	184	186	185	185	185	184	184	182
12	211	213	213	213	214	215	214	214	215	215	215	213
11	246	247	247	247	248	249	248	248	249	249	250	247
10	284	286	285	285	288	288	287	287	287	287	288	285
9	327	328	329	329	332	333	330	331	332	330	331	328
8	376	377	377	377	380	380	377	378	379	379	379	377
7	428	431	431	432	433	433	430	431	432	432	432	431
6	490	491	492	493	492	492	489	489	491	492	492	491
5	557	558	558	559	558	557	554	554	557	558	558	557
4	630	632	632	633	632	631	627	628	630	631	631	630
3	713	714	715	715	715	713	709	709	712	713	714	713
2	803	803	804	803	803	801	798	797	801	802	803	803
1	902	901	901	900	900	898	896	895	899	901	902	902

TABLE 24.—MEAN MONTHLY DENSITIES (GMS. PER CUBIC METRE) AT **Geometric** KILOMETRES.

Height in km.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	92	98	97		95		98	96	97	94	96	93
19	112	118	117	118	116		119	115	115	114	116	113
18	136	140	140	140	141	141	142	140	139	140	140	137
17	163	166	167	166	169	170	169	169	169	169	169	165
16	193	194	196	196	200	200	199	198	200	199	200	196
15	227	225	227	227	232	231	231	229	231	231	232	227
14	262	258	261	261	263	263	262	261	262	263	264	259
13	296	292	295	298	296	296	296	295	296	297	298	295
12	333	330	334	335	334	332	333	332	334	335	335	333
11	373	371	375	376	374	372	371	371	372	373	375	374
10	419	416	420	420	419	416	413	415	414	417	419	419
9	467	466	469	469	467	464	460	462	464	465	466	468
8	521	519	521	521	519	516	512	514	516	518	518	520
7	580	581	580	582	577	575	571	572	572	579	577	578
6	646	647	645	650	639	638	637	635	638	642	642	644
5	718	719	715	719	712	706	706	704	708	712	712	713
4	795	796	799	795	789	780	780	785	784	787	789	791
3	882	877	881	869	864	861	863	867	867	873	876	881
2	972	960	957	944	942	947	952	953	957	963	968	971
1	1,056	1,044	1,043	1,027	1,027	1,028	1,045	1,044	1,044	1,051	1,047	1,050

TABLE 25.—MEAN MONTHLY HEIGHTS (GKM.) CORRESPONDING TO PRINCIPAL ISOBARIC LEVELS.

Pressure (mb.).	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean.
100	16·09	16·30	16·19	16·20	16·23	16·30	16·28	16·31	16·29	16·25	16·25	16·20	16·25
200	12·08	12·13	12·11	12·12	12·19	12·23	12·18	12·18	12·21	12·19	12·19	12·12	12·16
300	9·40	9·44	9·43	9·45	9·49	9·50	9·46	9·46	9·49	9·48	9·49	9·44	9·46
400	7·37	7·39	7·40	7 41	7·44	7·43	7·39	7·38	7·42	7·41	7·42	7·39	7·40
500	5·71	5·72	5·73	5·75	5·75	5·75	5·70	5·69	5·74	5·73	5·74	5·72	5·73
600	4·30	4·32	4·35	4 33	4·33	4·31	4·27	4·26	4·31	4·31	4·32	4·31	4·31
700	3·08	3·09	3·10	3·10	3·10	3·07	3·03	3·02	3·07	3·08	3·09	3·07	3·07
800	1·99	1·99	2·00	1·98	1·97	1·95	1·93	1·92	1·96	1·98	1·99	1·99	1·97
900	0·99	1·00	0·99	0·98	0·97	0·96	0·94	0·92	0·96	0·99	1·00	1·00	0·97

TABLE 26.—MEAN MONTHLY AND ANNUAL TEMPERATURES (°A) CORRESPONDING TO PRINCIPAL ISOBARIC LEVELS.

Pressure (mb.).	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean.
100	94·0	00·0	94·5	94·0	91·0	93·0	93·0	95·0	94·0	93·0	92·0	93·5	194·0
200	17·5	22·0	19·0	17·0	20·5	22·5	20·0	22·0	21·0	20·0	19·5	19·0	220·0
300	39·5	41·0	39·5	40·0	42·0	44·0	44·5	43·0	43·5	42·5	42·5	39·5	242·0
400	53·5	55·0	55·0	55·0	57·5	58·5	59·0	59·0	/58·5	57·5	57·5	56·0	257·0
500	65·0	65·0	66·0	65·0	68·0	69·0	68·0	69·0	68·5	67·5	67·5	66·5	267·0
600	74·0	73·0	73·0	73·5	75·0	76·5	76·5	76·5	76·5	76·0	76·0	75·0	275·0
700	80·5	81·0	81·0	83·0	84·5	85·5	83·5	82·0	83·0	82·5	82·5	80·5	282·5
800	87·0	90·0	91·5	93·5	94·0	92·0	89·5	89·0	89·5	88·5	87·5	86·0	290·0
900	96·0	99·0	99·5	02·5	02·0	00·5	96·0	96·0	96·5	96·0	95·0	94·0	297·0

N.B.—The hundreds figure has been omitted in all the columns of *Table 26* except in that for the Annual mean.

MGIPC—M—VIII-3-1—1 2-9-34— 360.

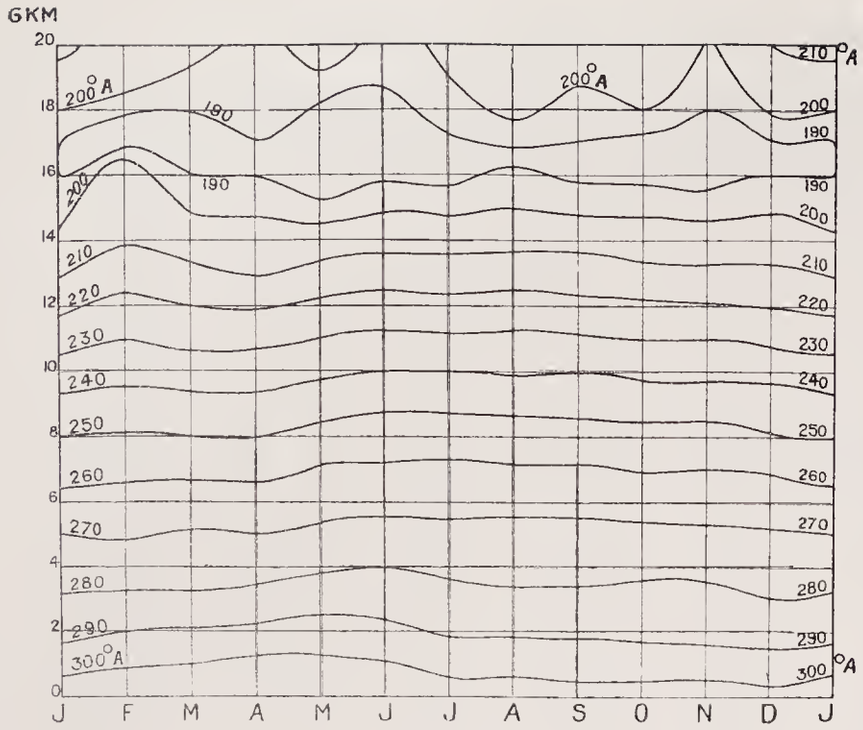


FIG. 1. SEASONAL VARIATION OF TEMPERATURE AT DIFFERENT HEIGHTS OVER POONA AND HYDERABAD.

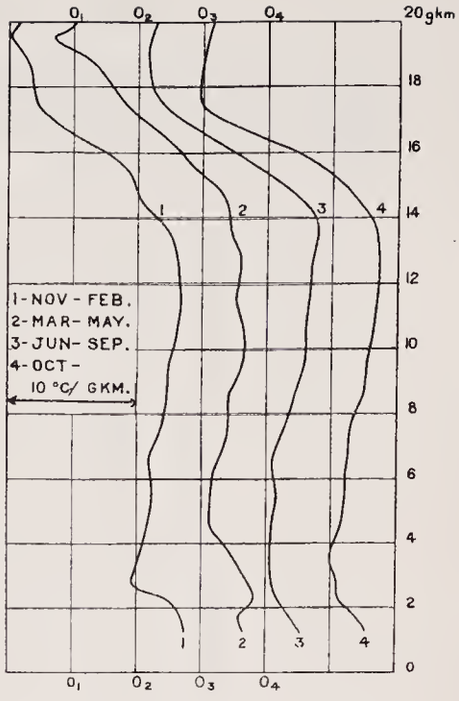


FIG. 2. VARIATION OF MEAN LAPSE-RATE WITH HEIGHT IN DIFFERENT SEASONS.

0_1 0_1 is the line of zero lapse-rate for curve 1, 0_2 0_2 for curve 2 and so on.

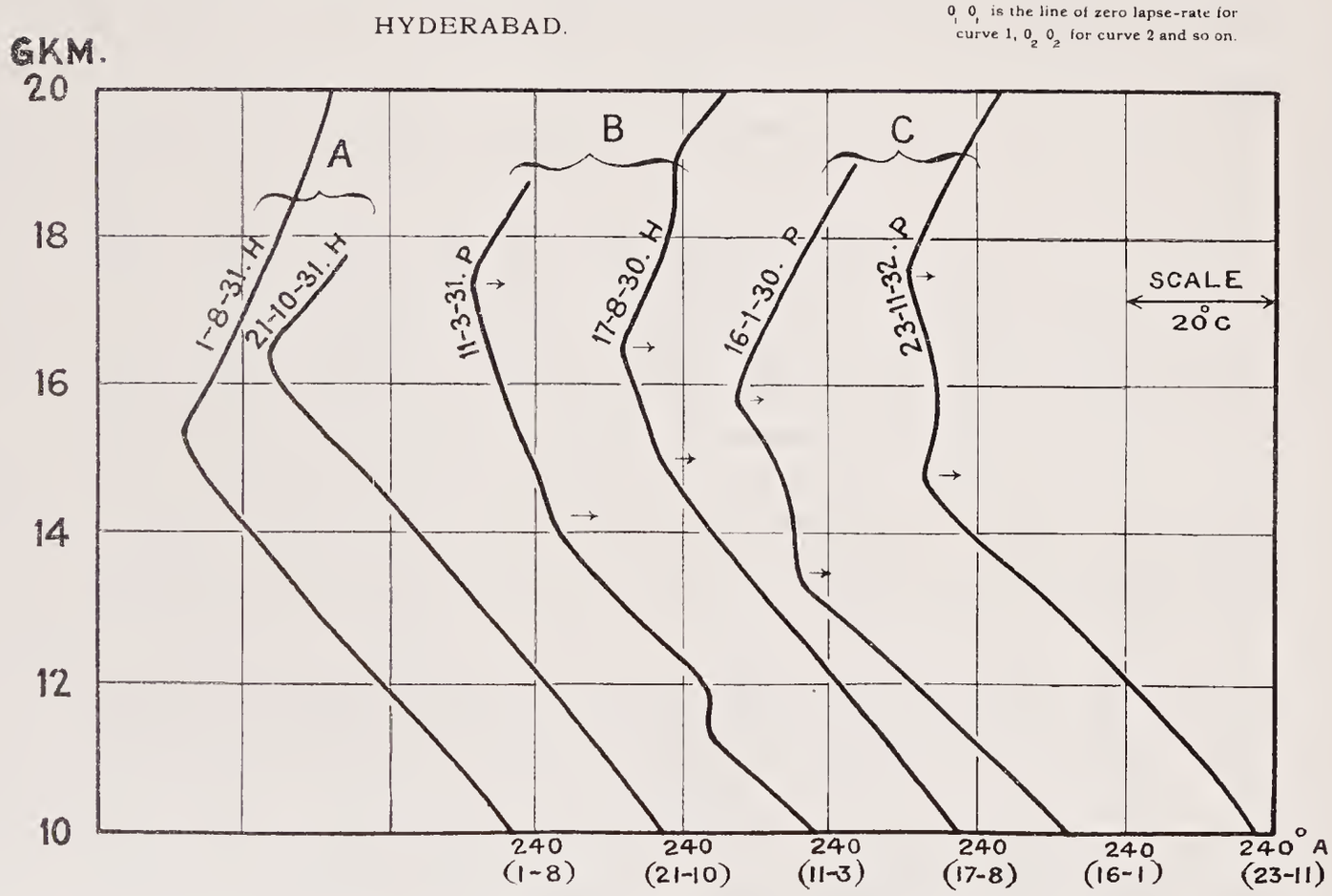


FIG. 3. HEIGHT-TEMPERATURE CURVES SHOWING DIFFERENT TYPES OF TROPOPAUSE AT POONA (P) AND HYDERABAD (H).

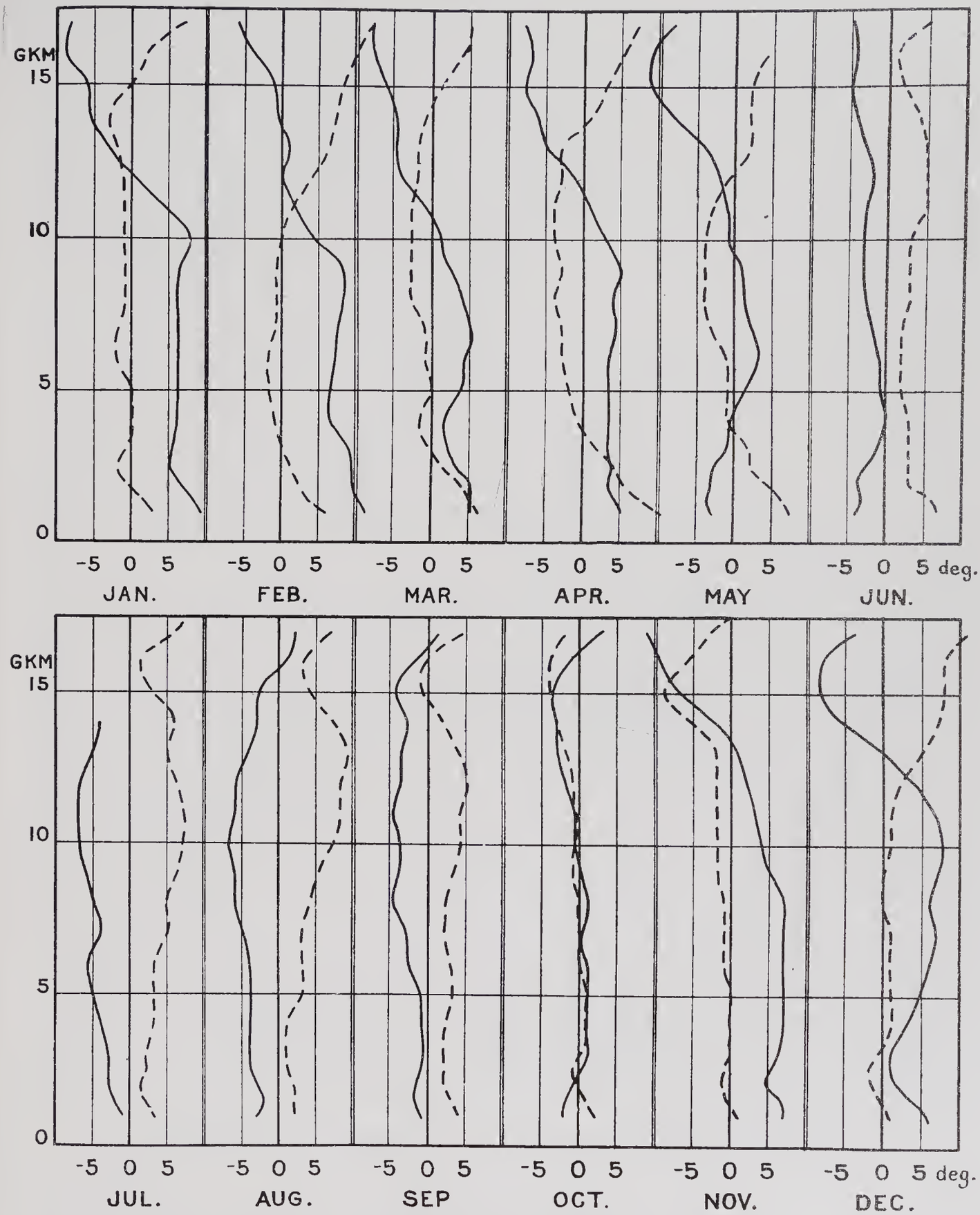
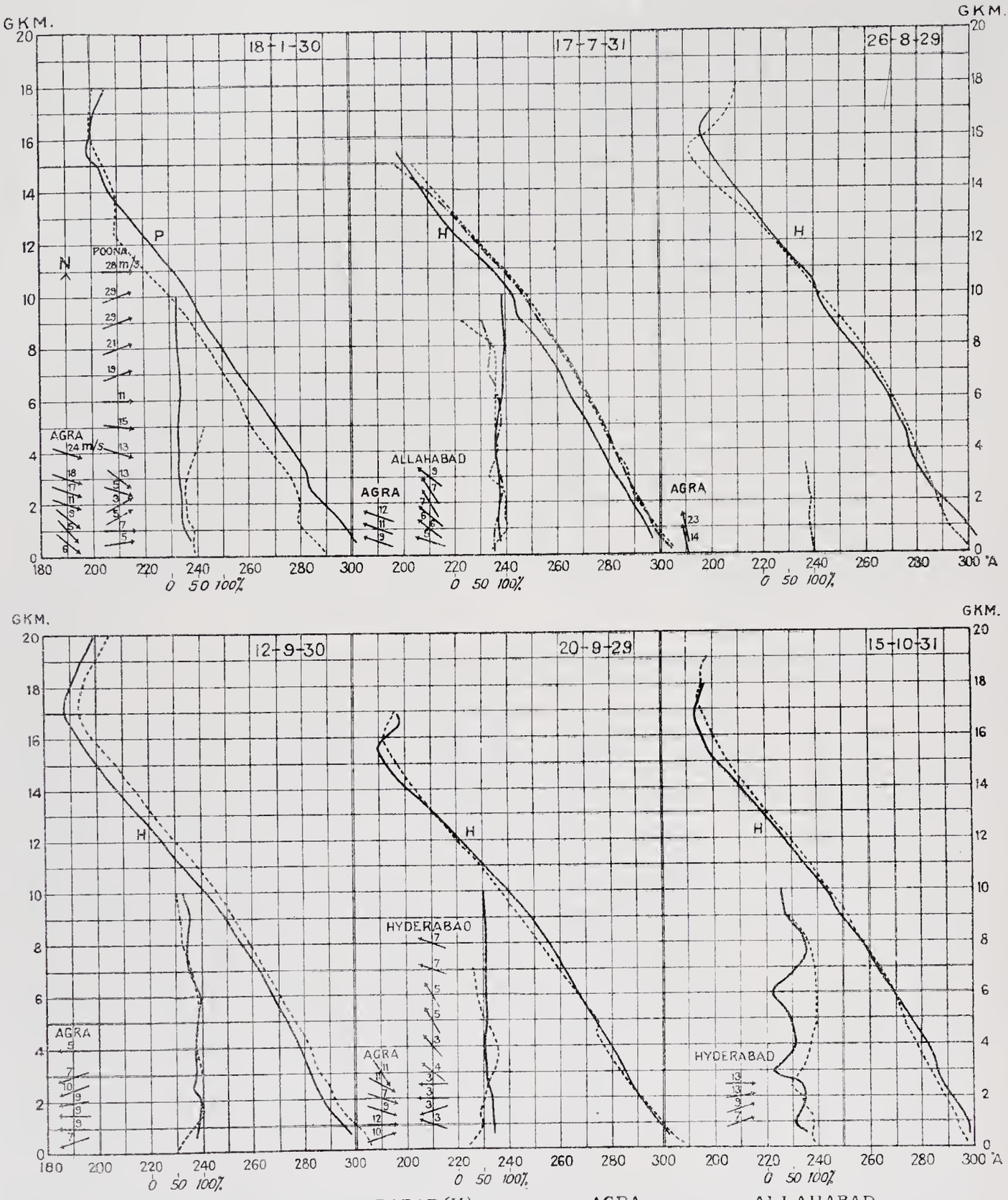


FIG .4. MEAN MONTHLY TEMPERATURE DIFFERENCES BETWEEN POONA, AGRA AND BATAVIA.

——— POONA—AGRA -------- POONA—BATAVIA

U.J.G.P.Z.O. Poona, 1934.



——— POONA (P) OR HYDERABAD (H) – – – – – – AGRA – · – · – ALLAHABAD.

FIG. 5. SOME NEARLY SIMULTANEOUS ASCENTS AT POONA OR HYDERABAD AND AGRA

(a) G P Z. O POONA, 1934.

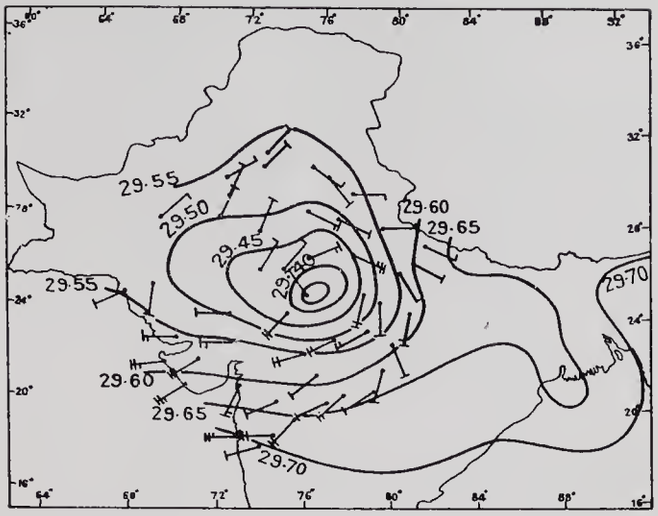


FIG. 6(a). SEA-LEVEL ISOBARS AND SURFACE WINDS AT 8 Hrs. ON 26-8-29

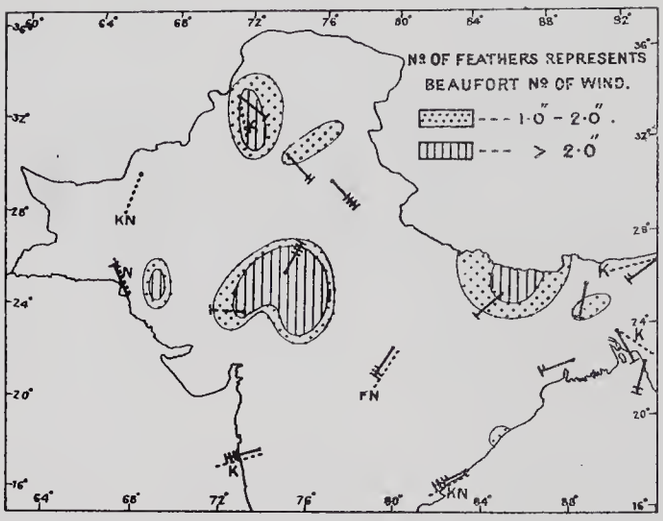


FIG. 6(b). UPPER WINDS AT 1 KM AND LOW CLOUD DIRECTIONS ON THE MORNING OF 26-8-29 AND RAINFALL IN NEXT 24 Hrs.

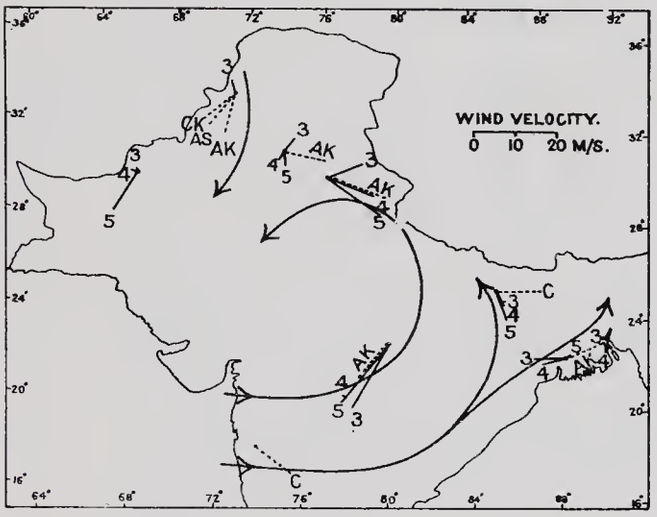


FIG. 6(c). WINDS AT 3, 4 AND 5 KM AND MIDDLE AND HIGH CLOUD DIRECTIONS ON THE MORNING OF 26-8-29.

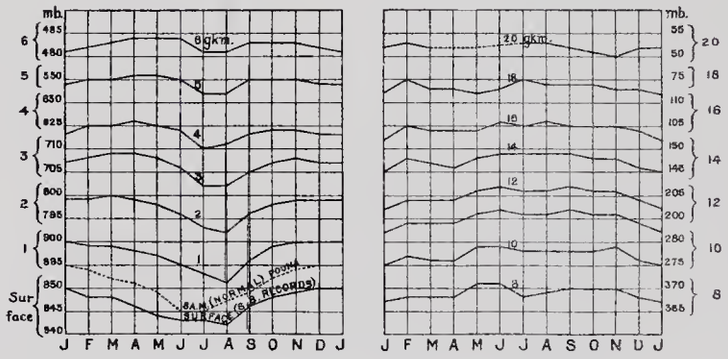


FIG. 7. SEASONAL VARIATION OF PRESSURE AT DIFFERENT HEIGHTS OVER POONA AND HYDERABAD.

(O)G P Z.O. POONA, 1934.

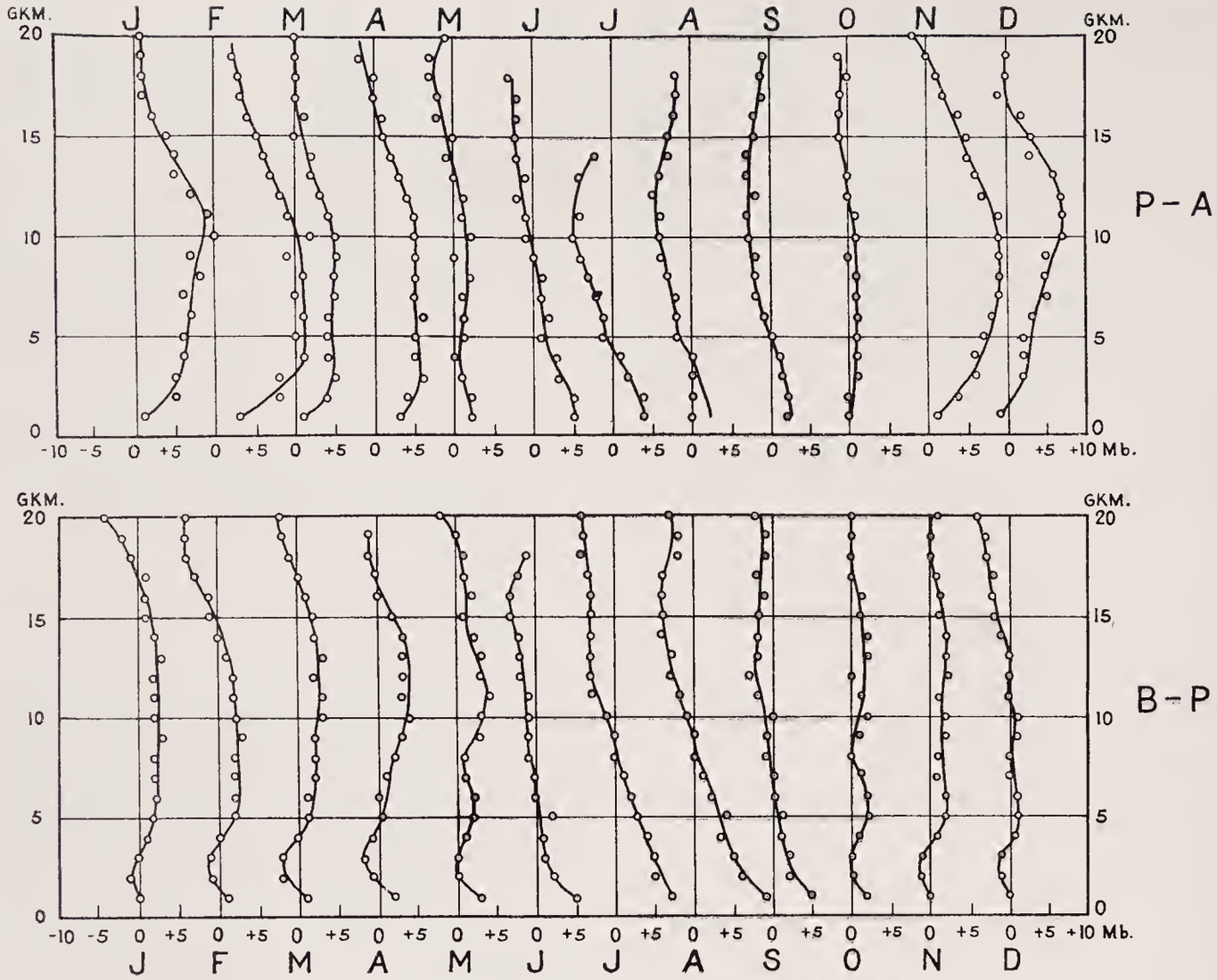


FIG. 8. MEAN MONTHLY PRESSURE DIFFERENCES BETWEEN POONA AND AGRA (P-A) AND BATAVIA AND POONA (B-P).

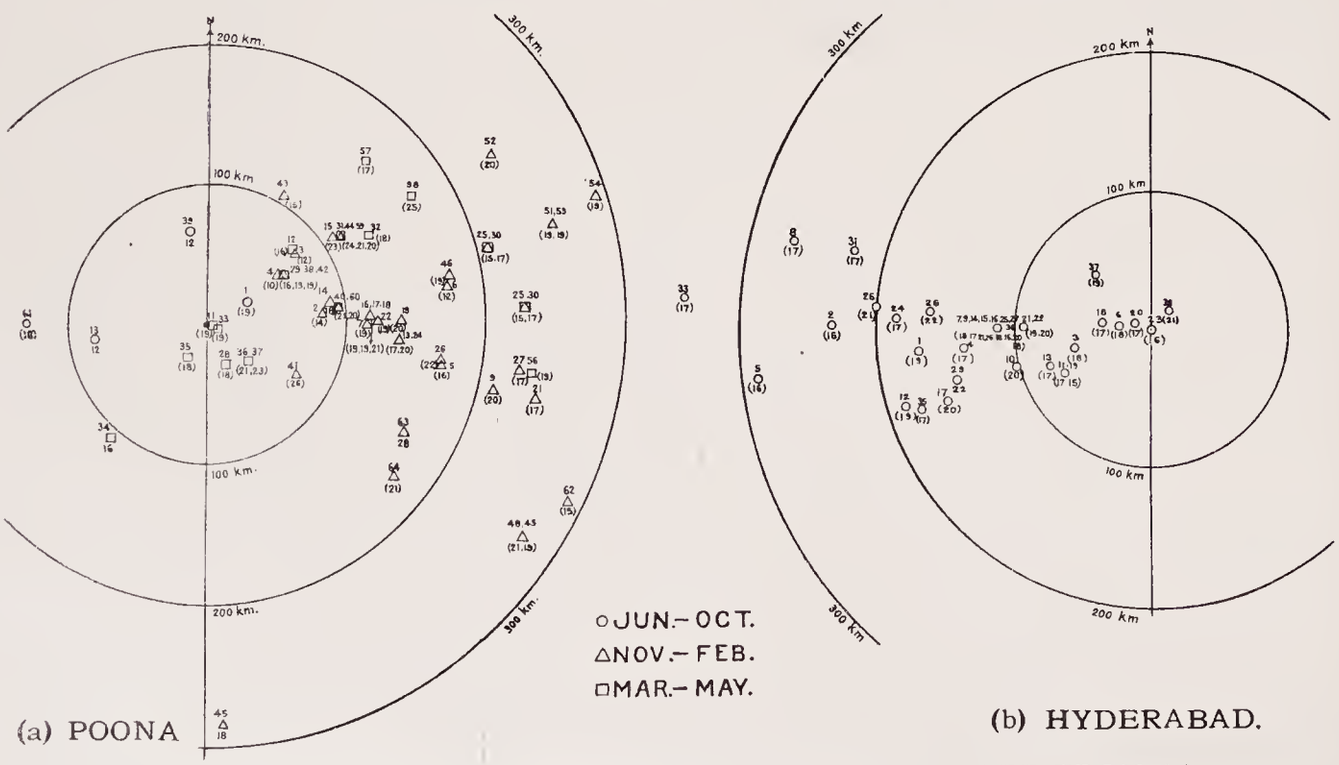


FIG. 9. PLACES OF FALL OF SOUNDING BALLOONS LET OFF FROM (a) POONA AND (b) HYDERABAD.

(a) G. P. I. POONA, 1934

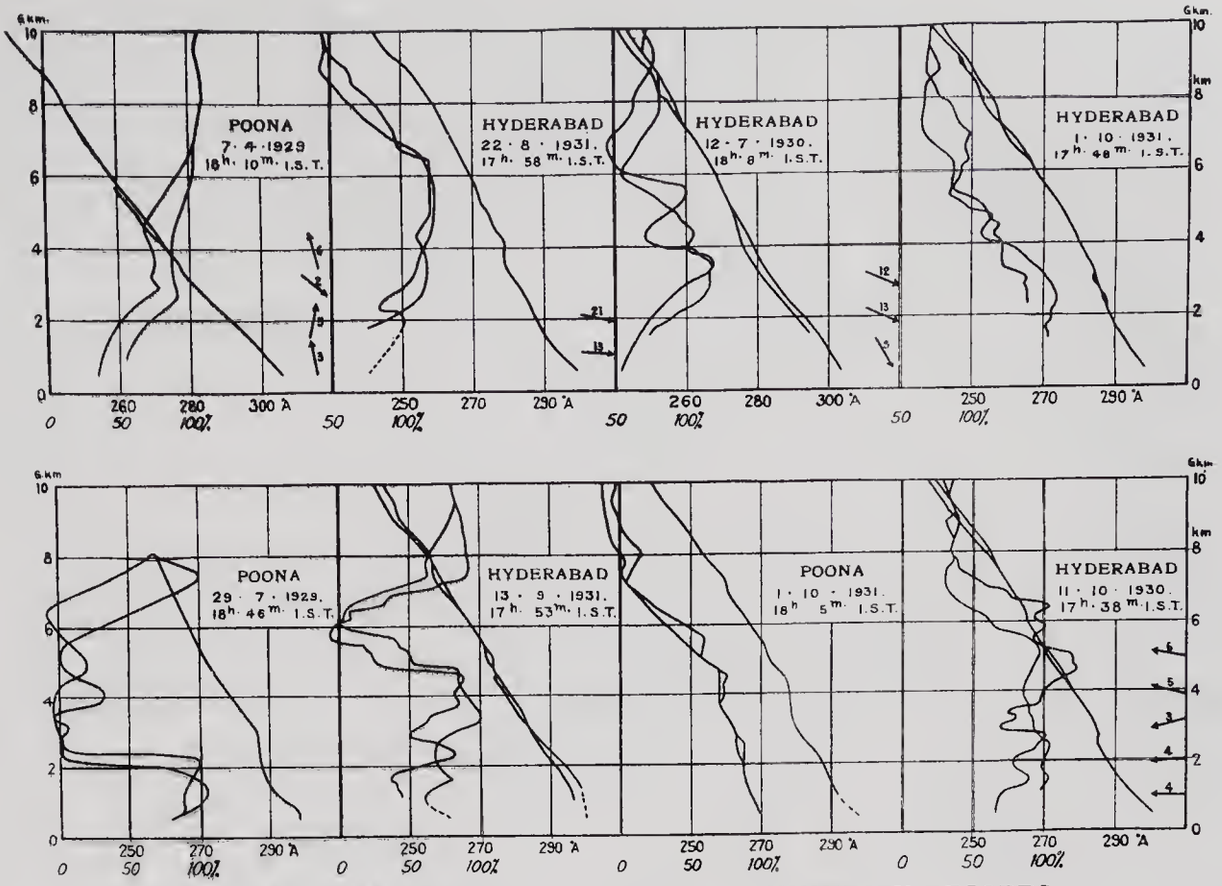


FIG. 10. SOME ASCENTS SHOWING TYPICAL HUMIDITY RECORDS.

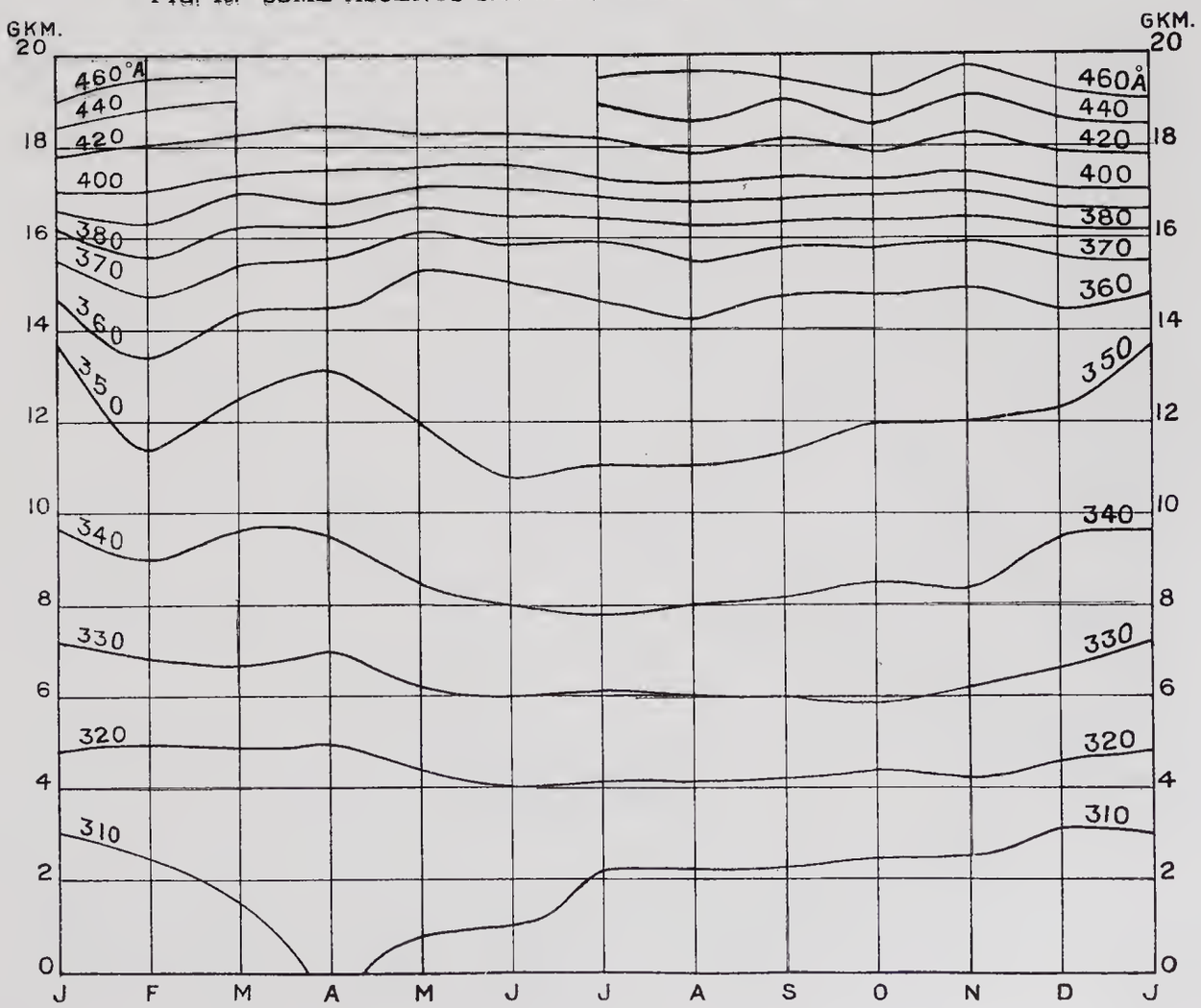


FIG. 11. SEASONAL VARIATION OF POTENTIAL TEMPERATURE AT DIFFERENT HEIGHTS OVER POONA AND HYDERABAD.

(0) G. P. I. O. POONA, 1934.

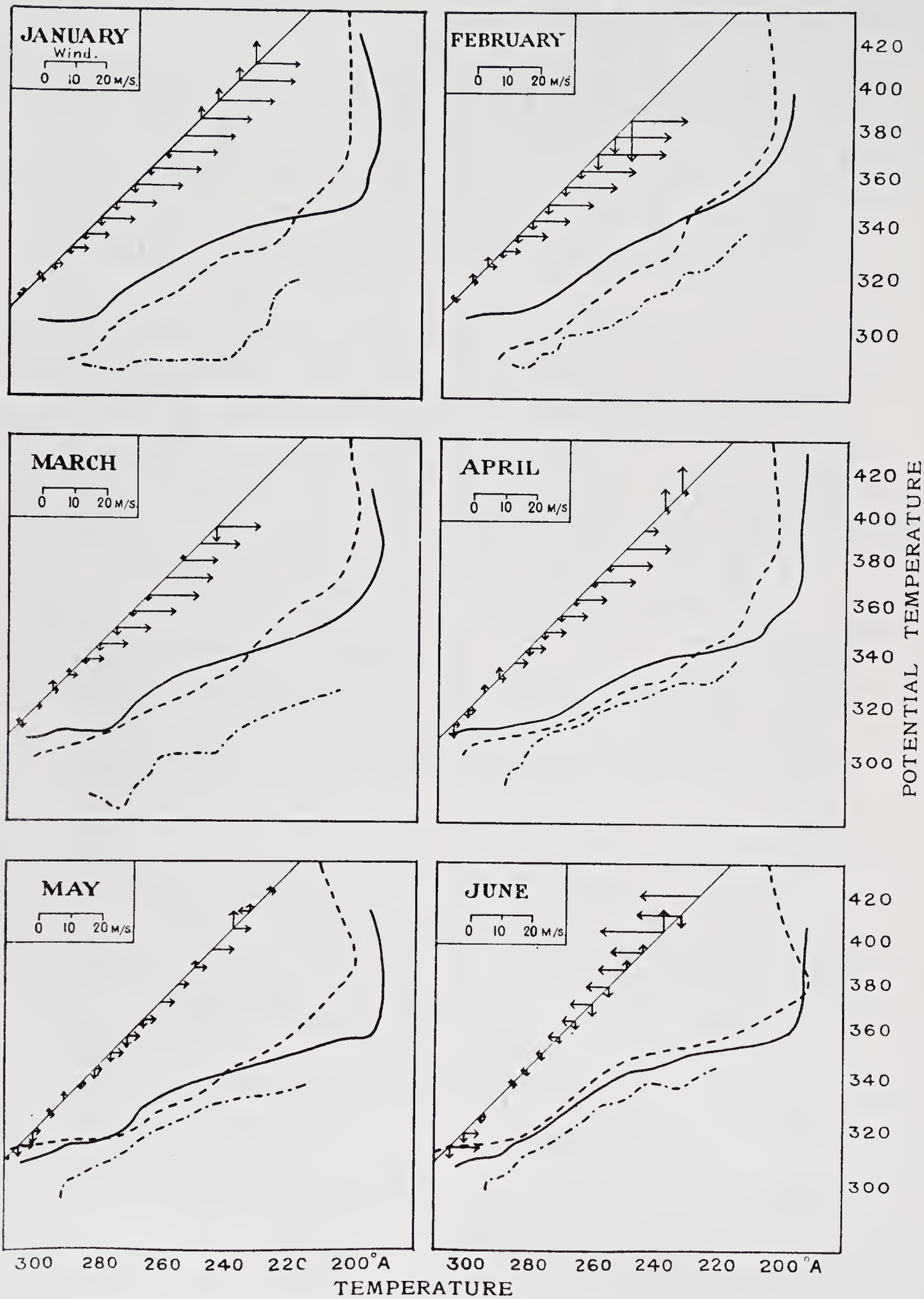


FIG. 12A. MEAN MONTHLY TEPHIGRAMS (JANUARY-JUNE).

THE FULL LINES REPRESENT THE TEPHIGRAMS FOR POONA OR HYDERABAD AND THE BROKEN LINES THOSE FOR AGRA. THE LINES WITH ALTERNATE DASHES AND DOTS REPRESENT THE DEW POINT PRESSURE DIAGRAMS FOR POONA OR HYDERABAD.

(a) G. P. Z.-U. POONA 1934

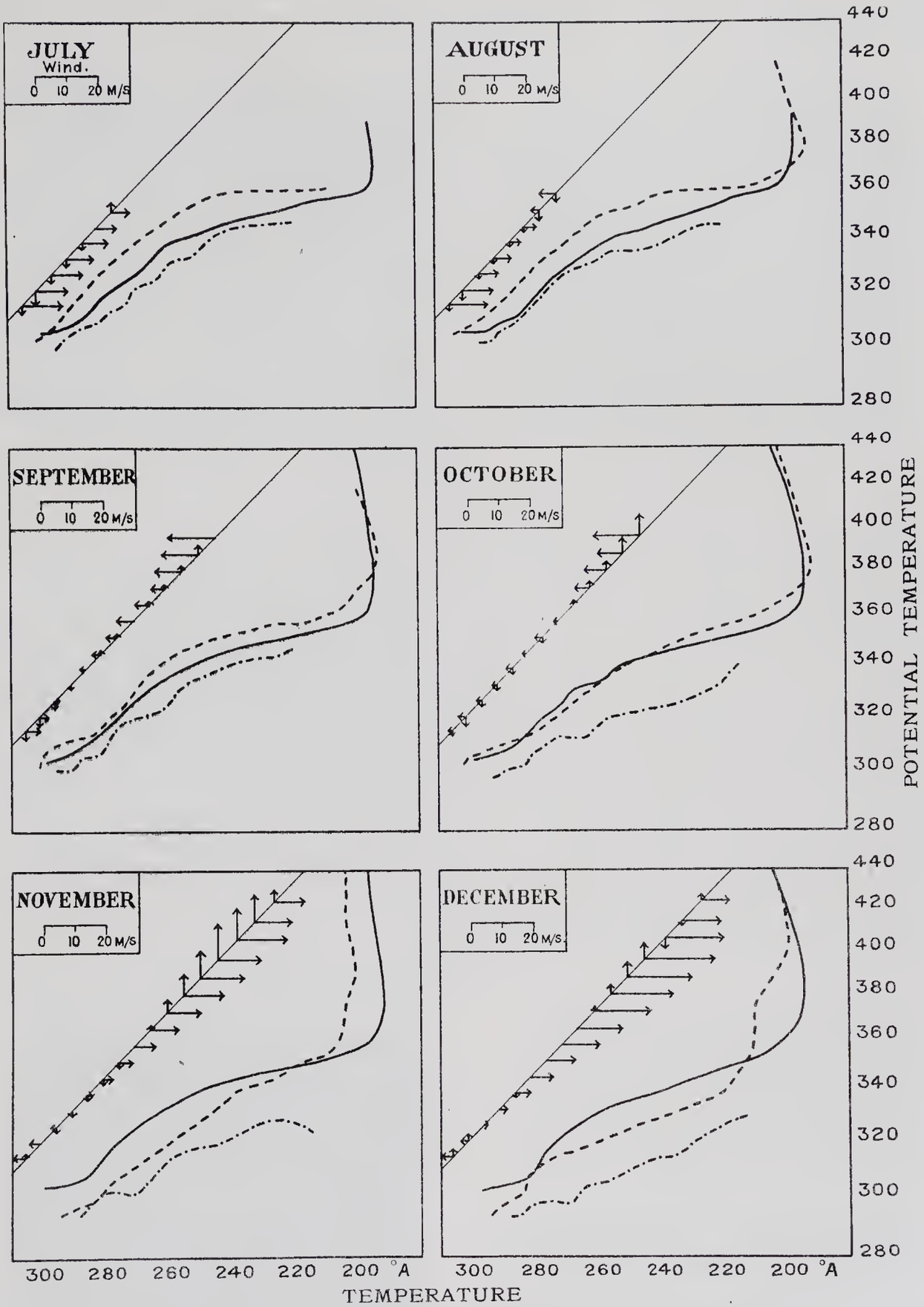


FIG. 12B. MEAN MONTHLY TEPHIGRAMS (JULY-DECEMBER)

THE FULL LINES REPRESENT THE TEPHIGRAMS FOR POONA OR HYDERABAD AND THE BROKEN LINES THOSE FOR AGRA THE LINES WITH ALTERNATE DASHES AND DOTS REPRESENT THE DEW-POINT PRESSURE DIAGRAMS FOR POONA OR HYDERABAD.

Convection Currents in an Unstable Layer of Fluid studied by Optical Methods.

THE convection currents set up in a thin horizontal layer of a liquid by an unstable distribution of density have been studied experimentally by many investigators. Following Bénard, the usual method of making the movements visible is to mix with the liquid fine particles of some shining substances such as aluminium or "gold" paint. Simple optical methods enable the phenomena to be studied in much greater detail.

A horizontal layer of liquid is obtained by floating it on clean mercury. The surface of a volatile liquid like ether or alcohol cools rapidly by evaporation resulting in an unstable distribution of density. With less volatile liquids, instability can be produced by placing the tray of mercury on a flat heater. If we reflect the divergent beam of light coming from a point source of light at the mercury surface at nearly normal incidence and receive the reflected beam on a screen, a pattern is formed on the screen showing the local deviations of optical thickness of the evaporating layer. Bright points and lines correspond to convergence of beam (cooler liquid or increased thickness) and dark points and lines to divergence. The liquid behaves as a composite lens backed by a plane reflector.

Figs. 1 to 5 show the successive stages of the appearance of the pattern on the screen as a layer of ether floating on mercury gradually gets thinner. When the layer is more than 4 mm. thick, prominent dark canals and rapidly moving thin bright filaments make their appearance. The former are regions at which the liquid ascends. When the thickness is 2–3 mm., the bright filaments converge to a series of lines or points surrounded by the dark canals. As the film gets thinner, the movement becomes less brisk, the dark canals get narrower and the bright spots in the middle of the cells get more concentrated and become connected together by bright lines. After a certain stage, the dark lines become invisible, but

Fig. 1.
Ether; thickness c. 7 mm.

Curr. Sci. 3, 473–475, 1935.

Fig. 2.
Ether, thickness c. 3 mm.

Fig. 3.
Ether; thickness c. 2 mm.

Fig. 4.
Ether; thickness c. 1 mm.

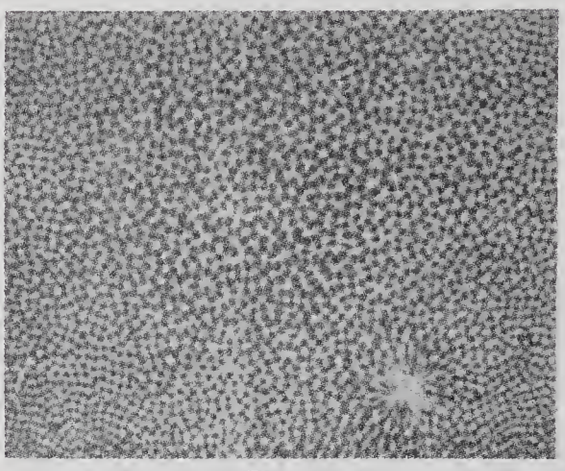


Fig. 5.
Ether; thickness c. 0·2 mm.

in this condition also, we have ascending movement in the middle of each bright-bordered cell and convergence and descending movement at the boundaries. A noteworthy feature of the vertical circulation in each individual cell is that the movement in the upper level is much more rapid than in the lower. This is easily verified by observation of floating specks of dust. As the film approaches the vanishing stage, the field is covered by a net-work of alternately bright and dark cells and just before vanishing, the film becomes continuous.

If instead of ether, we use a less volatile (and also more viscous) liquid like carbon tetrachloride, the movements are generally more sluggish but the sequence of changes is essentially the same; when the liquid layer is very thin, it divides itself into remarkably regular hexagons (Fig. 6). The regularity is

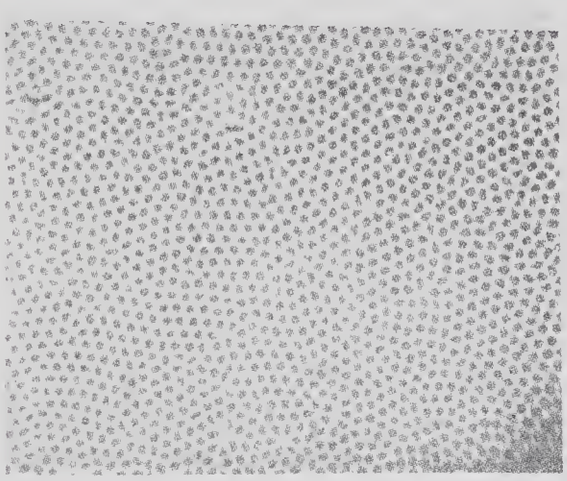


Fig. 6.
Carbon tetrachloride; thickness c. 0·2 mm.

dependent on a proper balance between density-gradient and viscosity.

If the unstable liquid has a translatory movement, the cells arrange themselves along the line of movement accompanied by characteristic changes of shape. Figs. 7 and 8 obtained with carbon tetrachloride

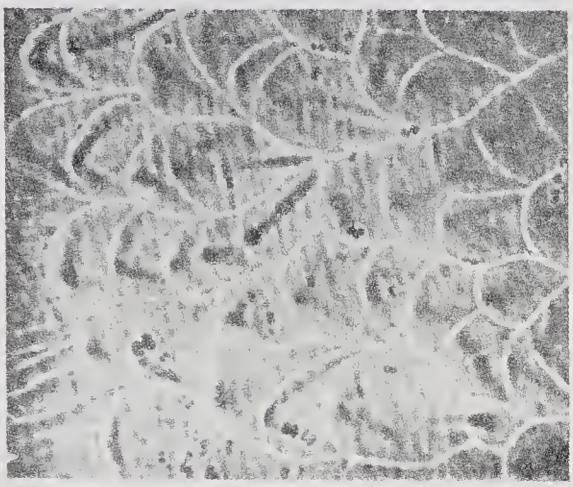


Fig. 7.

CCl_4 moving towards the right.

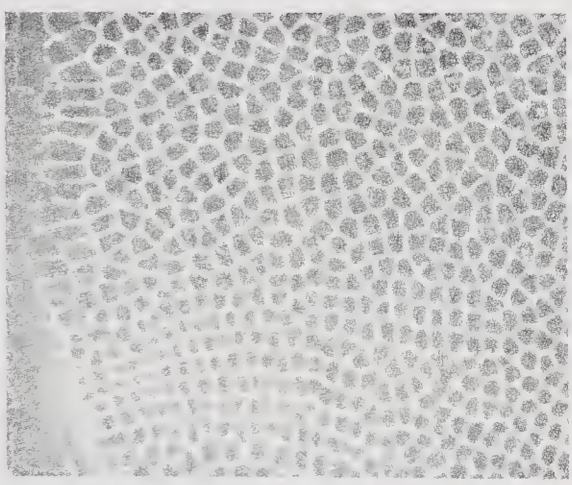


Fig. 8.

CCl_4 moving towards the right.

illustrate this. Their similarity to cloud forms has been studied by Mal, Walker, Phillips and others.

The influence of temperature-gradient, viscosity and heat-conditions of the liquid in determining the instability and the patterns of cell-structure is being investigated in the light of theories developed by Lord Rayleigh and H. Jeffreys. The Schlieren method can also be used to show up the cells, but the shadow method is simpler. Attempts are being made to apply these methods to study the vortices in gases.

K. R. RAMANATHAN.
V. N. KELKAR.

Poona,
April 4, 1935.

SOUNDINGS OF TEMPERATURE AND HUMIDITY IN THE FIELD OF A TROPICAL CYCLONE AND A DISCUSSION OF ITS STRUCTURE.

BY

K. R. Ramanathan, M.A., D.Sc.

(Received 25th April 1935.)

Summary.—In connection with the Bay of Bengal storm which crossed the north Madras Coast on 17th November 1933, a series of 10 ascents of sounding balloons carrying meteorographs were made from Madras. The data of temperature and humidity obtained from the records are discussed in the first part of the paper. The storm was preceded by an increase in the thickness of the lower moist layer which is usually present in this season and also by the arrival of warm moist air in the upper atmosphere above 8 gkm. With the continued approach of the storm, the lower moist layer increased in thickness and the lower surface of the upper layer descended. Near the centre of the storm, the two moist columns presumably joined up.

The second part contains a discussion of certain aspects of a tropical cyclone, such as the height to which it extends, the origin of its energy and the probable causes of lowering of pressure near its centre.

Introduction.

In November 1933, a depression formed in the south-east of the Bay of Bengal on the 14th, and following the usual westerly to northwesterly course, developed into a storm on the 16th and crossed the north Madras Coast very near Nellore to its north on the evening of the 17th. It weakened rapidly after entering land and the rainfall area moved into the Deccan and the central parts of the country. The track of the disturbance is shown in *Fig. 1.* In connection with this disturbance a series of sounding

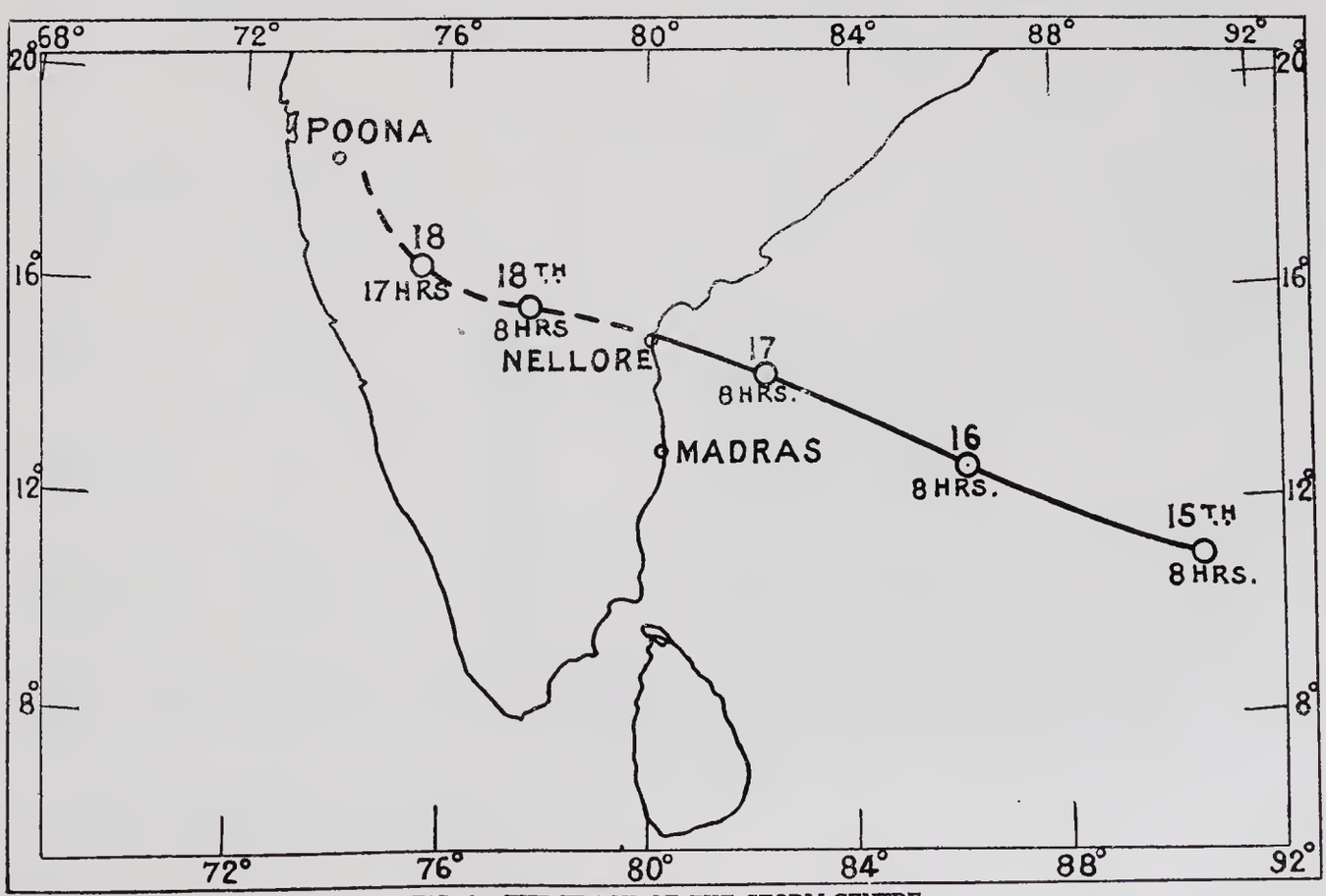


FIG. 1.—THE TRACK OF THE STORM-CENTRE.

B 2

Mem. Ind. Met. Dept. 26(5), 79–92, 1936.

balloon ascents were made at Madras and at Poona during the period 15th to 20th November 1933. In the present paper the results obtained from these ascents are summarised and this is followed by a discussion of the structure of a tropical storm.

The dates and times of ascents of the sounding balloons, the maximum heights reached and the distance and direction of the places of fall from the places of release are given in *Table I.* The positions of the Soundings on the 15th, 16th, 17th and 18th relative to the storm-centre are indicated in *Fig. 2.* It is unfortunate that the instruments

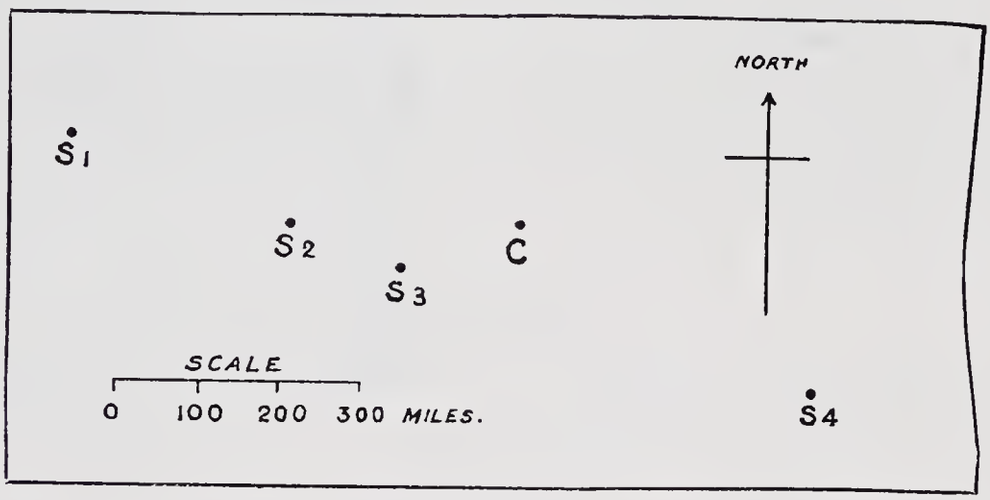


FIG. 2.—POSITIONS OF THE SOUNDINGS (S) ON THE 15TH, 16TH, 17TH AND 18TH RELATIVE TO THE STORM-CENTRE (C).

sent up from Madras on the evening of the 17th and on the morning of the 18th—the two that were nearest the centre of the storm—were not recovered.

TABLE 1.

Place.	Date.	Time hrs. I. S. T.	Maximum height (dynamic metres.)	Distance and direction of place of fall.
Madras . . .	15th November 1933 .	1716	18040	64 km. 246°
	16th November 1933 .	1800	17040	118 km. 251°
	17th November 1933 .	0404	17010	94 km. 228°
	17th November 1933 .	1801	Not recovered.	
	18th November 1933 .	0400	Do.	
	18th November 1933 .	1755	18340	115 km. 299°
	19th November 1933 .	0400	18800	115 km. 299°
Poona . . .	17th November 1933 .	1727	18440	92 km. 328°
	19th November 1933 .	0407	18040	43 km. 355°
	20th November 1933 .	1730	17070	80 km. 49°

The pressures, temperatures, and humidities at various levels obtained from the different ascents are given in the Appendix.

PART I.

Brief description of weather conditions associated with the storm.

Fig. 3 shows the curves of variation of surface pressure, temperature, humidity and vapour pressure at Madras on the 17th and 18th. In the same figure is also shown the rainfall at Madras and the curves of pressure at Nellore. This last curve and the sequence of weather at Nellore make it clear that we are dealing with a fully developed tropical cyclone. Some weather remarks recorded by the Nellore Observer on the 17th are extracted below :—

" From 1430 hrs. very strong squally wind from the north-west of force about 7 commenced, accompanied by rain. At 16 hrs. the wind attained a force of 10, many trees fell down and the rain was heavier. This continued till 1745 hrs. after which there was complete lull. The rain as well as wind stopped and the pressure began to show signs of rising. At 1800 hrs. the wind commenced again, blowing with force of 8—9, from the south in the beginning and from the southeast after half an hour, accompanied by rain. This continued till 0130 hrs. on the 18th."

It is interesting to note that there was considerable dissymmetry in the distribution of rainfall before and after the passage of the storm centre, the amount of rainfall registered at Nellore between 8 hrs. and 17 hrs. on the 17th being 3·17″ while that between 17 hrs. on that day and 3 hrs. on the 18th being only 0·50″. As is evident from *Fig. 2*, there is a corresponding dissymmetry in the Madras rainfall also.*

Upper air conditions over Madras during 15th to 19th.

The height-temperature and height-humidity diagrams of the ascents are given in *Figs. 4 and 5*.

The sounding balloon ascent at Madras on the 15th was made at 1716 hrs. ; at the time of the ascent, the sky was lightly clouded with Cu and Cist. The record shows a large lapse-rate of 9°C/gkm. in the first 1·45 gkm. followed by an isothermal layer with a thickness of about 0·5 gkm. The air had increasing humidity with height in the first 1·4 gkm. and was nearly saturated at the top as shown by one of the curves. The beginning of the inversion marked the boundary between the lower turbulent moistened air and the upper subsiding dry air. Above the inversion, the humidity was 15 to 30 per cent. with indications of a feeble maximum near 4 gkm. The limit of the troposphere was marked by an isothermal layer beginning at 15280 gdm ; the inversion began at 16700 gdm.

On the 16th also, the ascent was made in the evening at 1800 hrs. The cloud at the time of the ascent was Ast 6 and Stcu 4 (mammato-form). Earlier in the day, Cu and Ci were present. The humidity was nearly steady at about 60 per cent. till 1·2 gkm. and thereafter increased rapidly to saturation. The lapse-rate showed a marked decrease at 1·4 gkm. The top of the moist layer was at 2·6 gkm. in one curve and at 2·9 gkm. in the other. A pilot balloon sent up at 1600 hrs. showed a NNWly. to Nly. wind up to 1·2 km. and a NEly. wind at 1·5 and 2 km. The trajectories of air movement show that

* *See* B. N. Desai and S. Basu, ' Evidence in favour of non-symmetrical structure — Cyclones in Indian Seas ', Gerl. Beitr. Z. Geoph. 1933, 40, 1—10.

the northerly wind was coming direct from North India while the northeasterly above was coming across the Bay. Higher up, there were three significant increases of temperature, one beginning at 4·0 gkm. a second at 8·1 gkm. and a third at 14·0 gkm. The increase of temperature above 8·1 gkm. was accompanied by high humidity. Between the top of the lower moist layer near 2·7 gkm. and the bottom of the upper moist layer beginning at 8·1 gkm. there was thus comparatively smaller humidity. With the increase of temperature and moisture above 8·1 gkm. there was also an increase of lapse-rate between 10 and 13 gkm.

Of the two instruments that were sent up on the 17th, only the one released at 0404 hrs. in the morning was recovered. At the time of the ascent, the sky was overcast with Ast and Stcu and light intermittent drizzle had begun at 0230 hrs.* The important changes noticeable in the upper air conditions since the evening of the 16th are—

(1) The rise of the top of the lower moist layer to 3·7 gkm.

(2) An *increase* of temperature between 1·5 and 2·7 gkm. and a *decrease* between 2·7 and 6·2 gkm.

(3) The lowering of the upper moist layer to 7·0 gkm. and

(4) A large difference in humidity between the ascending and descending curves in the region 5-7 gkm. (It may be remembered that the place of fall of the instrument was 94 km. to the south-west of Madras.)

It will be seen from *Fig. 4* that the increase of thickness of the lower moist layer has broken down the inversion at its top. The decreased temperature between 2·7 and 6·2 gkm. would give rise to instability and seems to be of significance in the mechanism of the cyclone. The low temperature in this region may be due to (1) the cooling of the originally dry air by evaporation of direct precipitation or of particles of moisture brought into it from the region of rainfall by the process of mixing or (2) an *en masse* raising of dry stable air by on-coming monsoon air underneath. Both these processes were probably operative in the present instance ; both would cause an increase of relative humidity, but the former would raise the specific humidity also.

The first registration of upper air conditions after the passage of the depression inland was from a meteorograph sent up at 1755 hrs. on the 18th (*Fig. 5*). There was intermittent rain during the earlier half of the day, but the last spell terminated at 1230 hrs. and there was only some cirrus haze and a few pieces of cumulus at the time of the ascent. A pilot balloon which was sent up at 15 hrs. and reached a height of 1·7 km. showed south-easterly winds. The meteorograph record showed that—

(1) There was a region of small lapse-rate between 1·8 and 3·0 gkm. and an inversion at 3·4 gkm.

(2) High humidity was confined to below 2·2 gkm. and

(3) compared to conditions on the morning of the 17th, the temperatures on this day were lower from 1·5 to 2·6 gkm., higher from 2·7 to 5·2 gkm., and again

* One feature of the ascent on 17th November 1933 may receive comment here. Appreciable quantities of rain began to fall at Madras only after 7 hrs. on the 17th. The question of what causes the growth of cloud particles into the big drops which constitute rain has been considered by T. Bergeron and he has suggested that the process of aggregation takes place mainly at temperatures below the freezing point. The splitting of drops by air currents will be smaller in the case of solid particles and the decreased vapour pressure over ice as compared to that over water will make the ice particles grow at the expense of the particles of water. It is of interest to note that on the morning of the 17th the top of the lower moist air column had gone up to 3·7 km. where the temperature was only 4°C above the freezing point.

lower above 7·5 gkm. The stratosphere began with an inversion at 16300 dynamic metres.

Isopleths of temperature, potential temperature and equivalent potential temperature obtained from these ascents are drawn in *Figs. 6* (*a*), (*b*) *and* (*c*). Regions where the relative humidity was over 80 per cent. are indicated by shading in *Fig. 6* (*a*). In these regions, it may be expected that a small ascent would cause the air to follow a saturation adiabat. In the absence of heat exchanges by radiation or by mixing, a mass of air would keep its potential temperature constant so long as it remains unsaturated. The rise of temperature and of potential temperature between 4 and 7 gkm. on the 16th afternoon are to be explained as being due to adiabatic descent of dry continental air. Temperatures and humidities at the high level stations Coonoor and Kodaikanal show that at Coonoor on the mornings of the 16th and 17th and at Kodaikanal on the afternoon of the 16th and on the morning of the 17th the air was exceptionally dry.

Station.	Date.	Time.	D. B.	W. B.	R. H.
					Per cent.
Coonoor (5730 ft.) . . .	15	8 hrs.	62·0	58·8	84
	16	8 hrs.	61·7	50·0	44
	17	8 hrs.	63·0	51·0	43
Kodaikanal (7688 ft.) . .	15	8 hrs.	51·4	51·4	100
	16	8 hrs.	48·9	45·3	77
	16	17 hrs.	52·0	43·0	47
	17	8 hrs.	53·0	42·7	41
	17	17 hrs.	55·3	52·0	80

The rise of potential temperature above 8 gkm. with its attendant rise of humidity requires a different explanation ; the air at these levels is probably the air rising above the heavy rainfall area associated with the storm and carried by the easterly winds prevailing at these levels.

The changes of temperature observed on the 17th morning receive an explanation when we examine the diagram of equivalent potential temperature. Ordinarily in the tropics, owing to the decrease of vapour-pressure with height, the equivalent potential temperature decreases rapidly with elevation. This is especially marked above a " dry " inversion. After reaching a minimum, the E. P. T. again increases, owing mainly to the normal stable stratification of the atmosphere. Air of high E. P. T. near the ground is not generally capable of rising to the region of the same E. P. T. in the higher levels for two reasons : (1) so long as the ascending air is unsaturated, the movement of air is determined not by changes of equivalent potential temperature but by those of potential temperature and (2) when saturated air of limited volume ascends through an environment of dry air, it rapidly becomes unsaturated by the effect of mixing. But when the height of the lower moist layer increases, there comes a stage when the ascent from the lower to the upper level becomes easy. For example, on the 15th evening, the E. P. T. line 340°A was met with at 0·7 gkm. and again at 9·7 gkm. With the approach of the storm, the lower of these two levels went up and the upper one descended. On the

17th morning, the 340° line was found at 3·3 gkm. and again at 7·0 gkm. Moreover the relative humidity in the intervening layer had also increased. The course of changes suggests that later in the day, the equivalent potential temperature in the whole region between 3 to 6 km. was in the neighbourhood of 335°A. The probable trend of lines of flow are indicated by arrows. On the 18th afternoon, conditions somewhat similar to those on the 16th had again established themselves with dry air as low as 2·5 gkm. As the storm passed well to the north of Madras, the real warm sector air is partially missed by confining our attention to Madras upper air data. The defect can to a limited extent be remedied by calling in the aid of observations taken at Poona. The data of the ascents at Poona on the 17th, 19th and 20th show that on the 19th evening, the air of the warm sector had come over the place in the first 5 gkm. (vide *Fig. 9*). By replacing in *Fig. 6* (*c*), the Madras data of the 18th by the Poona data of the 19th, we can obtain a rough east to west section of the storm field along the latitude of Madras as it stood on the 16th afternoon. Such a modified diagram is shown in *Fig. 6* (*d*). Owing to mixing with the previously existing land air near the ground, the Poona data would give too low values of equivalent potential temperature in the first two gkm.

The most important features shown by the diagrams can be summarised as below :—

(1) There is a strong concentration of upward vertical movement in the neighbourhood of the centre of low pressure—the upward movement being predominantly in advance of the storm centre. As has been already mentioned, the rainfall associated with the cyclone was much greater in quantity before the passage of the low-pressure centre than after it.

(2) The warm air rising above the rainfall area and moving with the upper winds acts as a " leader " of the storm. This is shown by the rise of temperature and humidity above 8 gkm. even on the 16th.

(3) There is similarity in vertical structure between the tropical storm and the " occluded " cyclone of temperate latitudes, the dry air taking the place of cold air in the latter.

Two charts showing the detailed distribution of rainfall as recorded on the mornings of the 18th and 19th are given in *Figs. 7* (*a*) *and* (*b*). Upper wind charts and trajectories on the 17th, 18th and 19th are given in *Fig. 8*. The rainfall distributions on the 18th and 19th and the upper wind trajectories show that the dissipation of the storm on entering land was partly if not mainly due to dry land air coming from the south and destroying the humid-labile condition of the feeder-current.

Upper air conditions over Poona on 17th, 19th and 20th.

The cyclone entered land on the evening of the 17th, and on the 19th morning the residual low pressure wave was passing northwards over Poona.

On the 17th, the skies over Poona were clouded with Cist. The sounding balloon ascent on the evening of that day (*Fig. 9*) shows that temperatures were abnormally low from 5 to 15 gkm. The winds were weak northeasterly to easterly and southeasterly up to 6 gkm. and west-south-westerly above. The easterly current was mainly anticyclonic dry air but the increase of humidity above 4 gkm. indicates that between 4 and 6 gkm., moist air was probably beginning to be drawn in. The weather was unsettled on the 18th and light intermittent drizzle occurred during the night and next morning,

but there was no measureable rain by 8 hrs. on the 19th. Rain occurred in the afternoon intermittently from 1240 hrs. to 1930 hrs. The sounding balloon ascent on the morning of the 19th showed that since the 17th evening, temperatures had markedly decreased from the ground up to about 4 gkm. and the air was nearly saturated from the surface up to 5 gkm. (in one curve) and nearly dry above. There were inversions or sudden decreases of lapse-rate at 5·4, 7·7 and 12·1 gkm. This is similar to what occurred over Madras on the 16th, but there is no evidence of an upper layer of humidity. On the 20th evening, when the next ascent was made, practically all traces of the depression had disappeared except for some cumulus and moderately strong cumulonimbus. The temperatures at almost all levels were intermediate between those on the 19th and the 17th. There was high humidity from 1 to 3·2 gkm. above which it gradually decreased. The isopleths of temperature, potential temperature and equivalent potential temperature are drawn in *Figs. 10* (*a*), (*b*) *and* (*c*). The comparison of the tephigrams of the ascents at Madras on the morning of the 17th [*Fig. 11* (*a*)] and at Poona on the morning of the 19th [*Fig. 11* (*b*)] is interesting as showing the unstable conditions which prevailed over Madras and the stable conditions over Poona.

Changes of temperature near the tropopause.

At the time of falling pressure, both in the Madras and Poona ascents, there were marked increases of temperature for 2 to 3 gkm. below the original level of the tropopause. At neither place can it be said that there was a lowering of the tropopause although it is possible to interpret the inversion over Madras on the 16th and 17th near 14 gkm. as an incipient conversion of a normal tropopause of tropical latitudes into one of composite type (Type IV).*

PART II.

Some general considerations regarding tropical cyclones.

The characteristics of a tropical cyclone are a region of very strong winds (force about 10 in Beaufort Scale) and rapidly falling barometer round a small area of very weak winds near the centre of lowest pressure. Torrential rainfall is always associated with it, generally on one side of the storm centre. The central area of weak winds has comparatively fine weather and is 10-30 km. in diameter. Many investigators believe that the hurricane winds blow approximately in circles round the central calm region, but all do not share this view.† Recent investigations in India have shown that all tropical cyclones have associated with them an upglide front at which moist air ascends. The front may reach the ground or may be occluded, but the course of weather phenomena leaves little doubt that it exists. Fronts of the same character are found to occur associated with depressions which never develop into full-fledged tropical storms. We have therefore to consider that the storm stage is an incident in the development of a tropical depression which may or may not occur. *Fig. 6* (*c*) shows that in the inner region of a tropical cyclone, there is strong ascent of a well-fed lower moist air stream through

* Mem. Ind. Met. Dept., Vol. XXVI, part IV, p. 58.

† B. N. Desai and S. Basu, *loc. cit.*

a region unstable for ascending saturated air presumably into an upper current which rapidly carries away the air which feeds into it from below.

We shall now consider two important questions regarding a tropical storm :—

(*a*) How high does it extend and at what level is it deepest ?

(*b*) What is the source of energy of the storm ?

As regards (*a*), we should naturally expect a certain amount of variation from one storm to another. Pilot balloon observations in the vicinity of a storm are naturally scanty, but there is enough material available to show that strong cyclonic circulation exists to a height of more than 4 km. There are a few instances where 6 km. winds are also available (generally only on one side of the storm centre) which show cyclonic circulations. In this particular storm, there was a significant fall of pressure up to 7 gkm. even at a distance of about 100 km. from the storm centre ; the absolute values of pressure-fall were practically the same from the surface up to 4 gkm., but the ratio of the fall of pressure to the mean pressure at the level was greatest at 3 and 4 gkm. Although this gives a general idea of the conditions above a storm, we have to remember that our estimates are subject to certain limitations some of which are practically impossible to overcome. The nearest distance from the centre of the storm at which a balloon was released was 250 km. Owing to the movement of the balloon with the upper winds, the pressures and temperatures do not refer to points on the same vertical nor to the same instant of time. From general considerations, we should expect the tropical storm to have its origin and maximum intensity at the levels of maximum vertical convection. Naturally, this would not be at the ground where both ground friction and the solidity of the earth would prevent the maximum vertical movements being developed. In laboratory examples of tornadoes and in natural small scale cyclones such as dust-devils, an essential condition for formation is super-adiabatic lapse-rate. In the free atmosphere, super-adiabatic lapse-rates for dry air are practically unknown ; but lapse-rates lying between dry adiabatic and saturation adiabatic and with a sufficient supply of moist air underneath are common and can develop to explosion-point.

(*b*) The question of the energy of cyclones has attracted much attention particularly from the point of view of the cyclones of temperate latitudes. Margules investigated the development of kinetic energy in two simple cases, one in which two equal air masses with differing potential temperatures were initially lying side by side, and the other in which one air mass of lower potential temperature was superposed on another of higher potential temperature. He showed that with the temperature contrasts which are usually observable in the atmosphere, the first is much more likely to be the main source of the energy of storms of temperate latitudes. As a variant of the case (2), W. Littwin* investigated the kinetic energy that can be developed by the overturning of an air mass with super-adiabatic lapse-rate of temperature. He showed that if initially a column of air of height 3 km. has a lapse-rate of 12°C/km. then the re-distribution of mass which will be associated with the attainment of equilibrium will be attended with an increase of kinetic energy equivalent to a velocity of 15 m/s. Although instability for vertical movement of *dry* air occurs in the atmosphere only in the neighbourhood of insolated ground, instability for vertical movement of saturated air is fairly common especially under tropical conditions.

* W. Littwin : quoted in Koschmeider's Dynamische Meteorologie (1933), p. 336.

V. Bjerknes and others* consider that there are two possible ways in which the kinetic energy of cyclones can be generated. One is by the local concentration through wave-motion of pre-existing air-movement. This, although of significance for increasing the kinetic energy, is yet insufficient by itself to account for such large velocities as are observed. The second is by the conversion of the potential energy of the solenoidal field of pressure and density when the pressure is not a function of density alone. They conclude that " the attainment of large velocities in storms depends on the fact that a fast moving air mass can take part in work-generating circulation in a strong solenoidal field ".

D. Brunt† expresses his disagreement with the above view and considers that the term $-2\omega\frac{dF}{dt}$ in the expression for the rate of increase of circulation is the most important one for the growth of large-scale circulations in the atmosphere. ω is the angular velocity of the earth and F is the projection of the area enclosed by a material curve on the equatorial plane of the earth. If an area F′ lies on the horizontal plane at latitude ϕ, $F = F' \sin\phi$. Contraction of a horizontal material curve increases cyclonic circulation while its expansion increases anti-cyclonic circulation. From expressions that have been developed by Lord Rayleigh and D. Brunt, it is easy to calculate the order of velocities which may be expected from the operation of this cause.

If matter be removed from the centre of a circular disc of radius R_0 initially at rest with respect to the earth, and if, after a time, its radius has contracted to R, there would have been generated in the inflowing fluid, a cyclonic velocity whose magnitude at distance r from the centre of the disc is given by

$$v = \frac{R_0^2 - R^2}{r}\,\omega \sin\phi$$

$$= \frac{\omega \sin\phi}{r} \times \frac{\text{Quantity of matter removed expressed as area}}{\pi}.$$

Let us suppose that air equivalent to a fall of pressure of 10 mb. or 0·3″ over a circular area of diameter 400 km. is removed from its centre and let this removal take place from a thickness of the atmosphere equivalent to a fall of pressure of 200 mb. The contraction in area will be nearly

$$\pi \times 200^2 \times \frac{10}{200} \text{ sq. km.}$$

and the resulting tangential velocity at a distance of say, 100 km. from the centre will be

$$v = 200^2 \times 10^{10} \times \frac{10}{200} \times \frac{7{\cdot}3 \times 10^{-5}}{100 \times 10^5} \times 1/4 \text{ cm./sec.} = 36 \text{ cm./sec.},$$

where $\sin\phi$ is taken to have a value 1/4.

This mechanism, although of importance in initiating the cyclonic movement, is not apparently directly responsible for the growth of large velocities.

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* V. Bjerknes, J. Bjerknes, H. Solberg and T. Bergeron.: Physikalische Hydrodynamik, 1933, Ch. IV.

† D. Brunt, Physical and Dynamical Meteorology, 1934, p. 177. " It is thus not possible to explain the growth of large-scale horizontal circulations in the atmosphere by the reactions due to the gradients of pressure and density not being parallel to each other."

In tropical cyclones, we have to distinguish between the intense circular vortex of comparatively small diameter and the extensive disturbed field surrounding it. The kinetic energy of the latter probably arises from the annihilation of isobaric-isosteric solenoids which are mainly created by the unstable superposition of unsaturated air over a layer of saturated air. The observed kinetic energy in the inner core can at least qualitatively be accounted for by the pressure field. A velocity of 40 m./s. at a distance of 100 km. from the cyclonic centre would be in equilibrium with a pressure gradient of 21 mb./degree assuming that in a tropical cyclone at such a distance from the centre, the geostrophic component of the wind can be neglected. The main problem is, how is the pressure field produced and maintained ?

A study of the weather charts shows that when a thick moist column of air advances towards higher latitudes in the northern hemisphere the low pressure area is formed in the left hand corner of the advancing moist column. Near the tropical " warm " front, there is a region of very heavy rainfall. Above this area of rainfall, there should be a large and rapid increase of temperature. Calculation shows that one inch of rainfall will liberate a quantity of heat which would be sufficient to raise the temperature of the whole thickness of the atmosphere above a place at sea-level 6°C. The expansion of the air above the region of rainfall will make the air-movement in the upper layers (*Fig. 12*) divergent. We know from the dynamics of a warm front that the cold air in advance of the front will be accelerated towards the left. At the left hand corner of

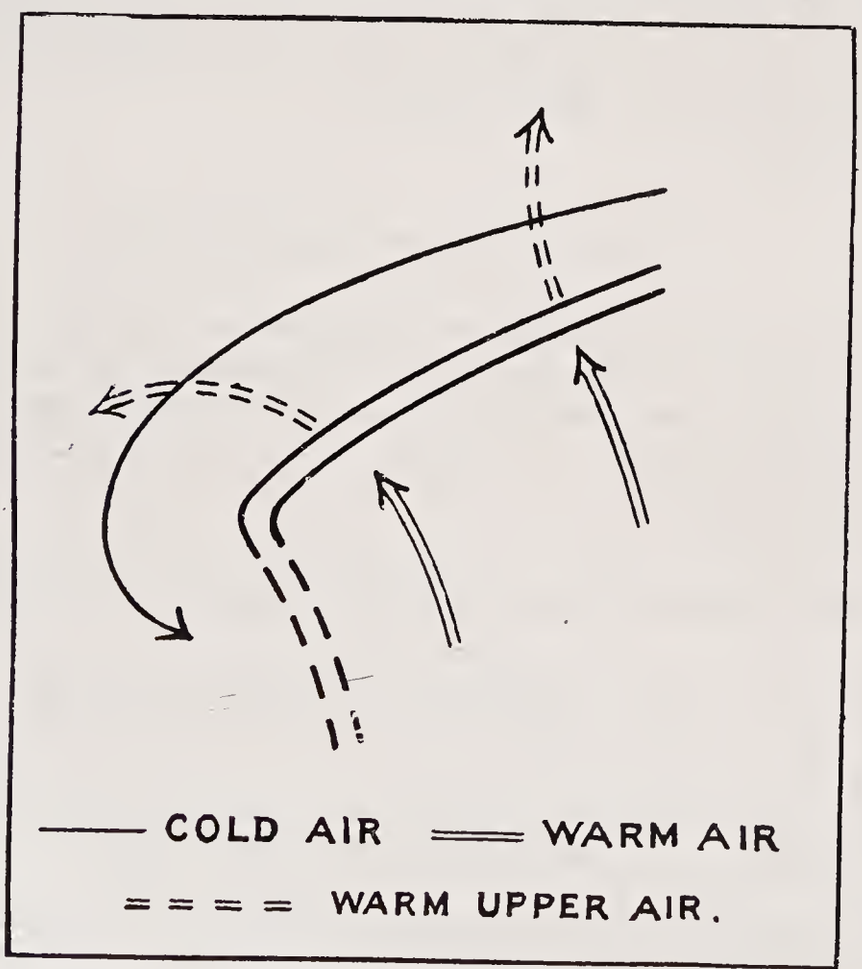


FIG. 12.

the front, there will therefore be formed both in the lower cold air and in the upper warm air a cyclonic whirl. The centrifugal action of the winds will tend to keep the denser air in the upper layers away from the axis and accumulate the warmer air in the central regions of the whirl*. Thus the pressure gradient round the centre will grow. The ultimate lowering of pressure will depend on the excess of temperature inside. In order to produce a lowering of pressure of 2 cm. of mercury in the interior of a depression the mean temperature of the whole atmosphere should rise by about 7°C. If only half the thickness of the atmosphere is involved, the excess of temperature will be 14°C. Most of this rise of temperature will be caused by the latent heat released by rainfall but part may be due to adiabatic descent in the centre of the low. It may be remembered that there is no agency known to us as effective as rainfall for rapidly increasing the temperature of large masses of air.

A lowering of pressure can also be caused by a west to east velocity over the rotating earth or a downward acceleration of the air. The equation governing the pressure lapse in a vertical direction† is given by

$$\frac{dw}{dt} - 2\,\omega\, u\, \cos\phi = -\frac{1}{\rho}\frac{\delta p}{\delta z} - g, \text{ or}$$

$$-\frac{1}{\rho}\frac{\delta p}{\delta z} = g + \frac{dw}{dt} - 2\,\omega\, u \cos\phi$$

where the positive direction of x is towards the east and that of z vertically upwards. In the static atmosphere, the second and third terms on the right-hand side of the second equation vanish. Let us now consider the relative magnitudes of all the terms in the neighbourhood of a tropical cyclone. As pointed out by Brunt, the effect of the term involving earth's rotation is negligible even when the zonal wind is as much as 100 m/sec., being then only $1{\cdot}4 \cos\phi$ cm/sec^2. If there should be a lowering of pressure due to vertical movement, the acceleration should be downward. It is known that the central region of a tropical storm is often marked by absence of rain and comparatively less cloudy skies. Abnormal dryness is also sometimes experienced in such regions. All these indicate a descending movement of air. We have however no reliable estimate of the magnitude of the downward accelerations. In stormy weather, it is known that sounding balloons with normal rates of ascent of about 5 meters per second are sometimes carried downwards for vertical distances of 5-6 km. If this downward velocity develops within a height of 3 km., the corresponding acceleration will be given by $w^2 = 2\frac{dw}{dt}h$ or $\frac{dw}{dt}$ will be about 0·4 cm/sec.^{2} An estimate of upward acceleration in hailstorms has been made by Brunt. He has shown that in order to raise a spherical hailstone of radius 3 cm. in an ascending current, a vertical upwards velocity exceeding 55 m/sec. would be required. If this velocity is developed within a distance of 3 km., the acceleration will be 50 cm/sec.^{2} This is by no means negligible compared with g (980 cm/sec.^{2}) and if it extends over a height of the atmosphere corresponding to 1/5 of its total mass, the change of pressure experienced at the earth's surface would be $1/5 \times 50/980 \times 76$ or about 0·8 cm. of mercury. Although sudden rises of pressure of 2 or 3 mm. of mercury are commonly

* V. Bjerknes, On the Dynamics of the Circular Vortex, etc., Geof. Publ. II, No. 4, Kristiania 1921. p. 43.
† D. Brunt, Physical and Dynamical Metcorology, p. 268.

met with in connection with thunderstorms and hailstorms, and it is possible to explain them as being due to vertical acceleration of air, no exceptional sudden rises of pressure have been noted in the region of torrential rainfall of a tropical cyclone. It would therefore be unreasonable to explain the lowering of pressure in the central region of a tropical storm as being due to a corresponding downward acceleration of air.

The general conclusion of this discussion is that the central vortex of a tropical cyclone is caused by the concentration of warm air in the upper levels in a definite region connected with a tropical up-glide front, heavy rainfall being mainly responsible for the rapid increase of temperature over a limited region.

The storm winds round the cyclone will tend to keep the warm air inside protected against rapid dissipation. The conditions that will help to fill up the vortex are (1) a decrease in the supply of moist air at the front leading to a diminution of rainfall and hence of the supply of warm air in the upper air and (2) inflow of air into the low caused by ground-friction and consequent undergradient winds.

Conclusion.—Apart from theories, the prime necessity for a fuller understanding of tropical cyclones is the collection of more data of temperature, humidity and air movement at as many levels in the atmosphere as possible in the neighbourhood of such cyclones. The east coast of Peninsular India is visited every year by one or more storms coming directly from the sea and both topography and upper winds are favourable for the recovery of a good percentage of sounding balloons. It is hoped that more opportunities will be available for the study of such storms.

The thanks of the author are due to the staff of the Upper Air Section at Poona and to the assistants and observers at Madras for the part they had in the calibration, sending up and the recovery of the instruments and the working out of the records. The help of Mr. K. P. Ramakrishnan, Assistant in the Upper Air Section, Poona, has been specially valuable in the preparation of the paper. His thanks are also due to Dr. C. W. B. Normand, Director General of Observatories for his kind interest in the work.

APPENDIX 1.

Pressures, temperatures and humidities at different levels over Madras.

Madras, 15th November 1933 at 1716 hrs.				Madras, 16th November 1933 at 1800 hrs.				Madras, 17th November 1933 at 0404 hrs.				Madras, 18th November 1933 at 1755 hrs.				Madras, 19th November 1933 at 0400 hrs.			
L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %
Ground	1008	299·8	60	Ground	1007	298·0	60	Ground	1005	298·0	56	Ground	1012	299·2	88	Ground	1011	295·4	97
500	951	95·0	72													500	953	93·0	..
1000	896	90·2	79	1000	896	93·6	77	1000	894	92·0	92	1000	900	93·0	70	1000	900	91·0	69
1450	850	86·0	61	1450	850	89·8	96	1060	890	91·8	93	1500	850	90·2	72	1500	849	89·4	69
1500	844	86·0	56	1500	845	89·5	96	1500	842	90·2	84	1800	820	87·6	67	2000	798	87·8	23
2000	795	86·0	23	2000	796	87·0	97	1870	810	90·0	85	2000	800	86·6	69	2180	780	87·5	21
2500	748	84·5	21	2500	749	84·4	86	2000	792	88·2	86	2500	753	84·2	30	2500	750	86·0	15
3000	702	82·6	18	2600	740	83·5	79	2500	746	85·2	90	3000	709	84·2	28	3000	706	83·6	15
4000	620	77·4	21	3000	702	83·2	52	3000	701	81·6	95	3470	670	80·6	17	3920	630	79·5	15
4550	580	73·0	23	4000	620	78·0	30	3660	650	77·5	93	4000	627	78·5	15	4000	624	78·8	25
5000	547	70·4	22	4750	565	75·8	32	4000	620	76·0	82	5000	552	72·5	18	5000	550	71·5	34
6000	480	64·2	19	5000	549	74·0	32	5000	547	71·4	65	6000	485	66·6	22	6000	483	65·5	32
7000	420	57·0	21	6000	482	67·0	40	5110	540	70·8	59	7000	424	60·5	19	6700	440	62·0	30
8000	366	50·2	27	7000	422	58·4	53	6000	480	66·6	64	7440	400	57·6	15	7000	423	60·2	30
9000	318	42·8	29	8000	369	51·0	79	7000	420	60·0	91	8000	370	52·5	21	8000	368	52·4	31
10000	275	34·8	26	8070	365	50·4	83	7130	415	59·6	91	9000	322	44·0	22	9000	320	44·4	31
11000	236	26·8	25	9000	320	46·0	85	8000	368	53·8	88	10000	279	36·0	16	10000	277	36·4	29
12000	203	18·5	25	10000	278	39·6	85	9000	320	46·2	85	11000	240	26·6	15	11000	237	27·0	30
13000	172	10·4		11000	240	31·2	84	10000	277	38·2	82	12000	205	18·4	16	12000	204	20·0	30
14000	145	01·2		12000	205	21·6	83	11000	239	29·8	79	13000	175	09·6		13000	174	10·8	
15000	122	194·8		13000	174	12·0		12000	204	21·4	76	14000	147	00·0		14000	147	02·0	
15280	116	93·2		14000	147·5	02·8		13000	174·5	12·0		14700	130	194·7		15000	123	194·0	
16000	102	92·7		14220	142	02·8		13600	158	07·2		15000	123	92·5		15520	112	92·0	
16700	90	93·5		15000	124·5	197·4		14000	147·5	04·6		16000	102	87·5		16000	103	94·0	
17000	85·5	95·6		15730	109	192		14440	137	02·6		16300	97	86·5		17000	86	96·5	
18000	71·5	02·8		16000	104	192		15000	124	196·7		17000	86	91·8		17780	75	200·1	
				17000	86·5	195·8		15200	120	94·7		18000	71·3	97·0					
								16000	104	92·5									
								16200	100	93·0									
								17000	87	202·0									

APPENDIX 2.

Pressures, temperatures and humidities at different levels over Poona.

Poona, 17th November 1933 at 1727 hrs.				Poona, 19th November 1933 at 0407 hrs.				Poona, 20th November 1933 at 1730 hrs.			
L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %
Ground	948	299·9	48	Ground	949	293·1	87	Ground	950	300·7	64
1000	898			1000	898	88·5	100	1000	900	294·2	86
1440	852	90·2	43	1500	846	87·2	99	1500	849	90·0	100
1500	846	90·0	42	2000	797	85·0	97	1670	832	88·4	100
1780	820	89·0	41	2500	750	82·4	99	2000	800	86·4	100
2000	798	88·2	36	3000	705	80·4	92	2500	752	83·9	97
2500	751	85·0	32	3020	704	80·0	91	3000	708	81·2	97
3000	707	83·2	34	3650	650	77·4	78	4000	624	76·0	73
4000	624	77·0	43	4000	622	76·0	80	4450	590	73·6	57
5000	550	69·2	53	5000	548	70·0	69	5000	550	70·0	46
6000	482	62·6	55	5400	520	67·2	39	5760	497	64·0	39
7000	422	55·8	52	6000	481	66·4	25	6000	482	63·0	37
8000	367	48·0	51	7000	421	57·2	24	7000	422	56·5	30
9000	318	39·8	51	7600	388	51·2	22	8000	367	48·7	30
10000	275	32·0	52	8000	367	50·4	20	9000	319	40·8	29
10630	250	27·8	54	9000	319	42·0	19	10000	275	32·6	28
11000	236	25·0	53	9280	306	39·4	18	10120	270	31·8	28
12000	201	14·8	52	9700	288	37·2	19	11000	236	24·6	28
13000	171	06·8		10000	275	34·4	19	12000	202	15·6	28
14000	144	198·3		11000	236	25·0	20	12050	200	15·2	
14830	123	92·4		12000	202	16·6	21	13000	172	08·4	
15000	121	92·4		12130	198	15·4		13400	160	05·0	
15280	115	93·5		13000	172	11·5		14000	145	01·2	
16000	101	91·3		13050	171	11·4		14700	128	195·0	
16020	100	91·5		14000	146	04·6		15000	122	93·1	
16700	89	94·5		15000	122·5	197·7		15580	109	91·3	
17000	85	94·8		16000	102	93·2		16000	101·5	94·0	
17900	72	95·3		16720	90	91·5		16600	91	94·4	
18000	71	95·6		17000	86	92·7		17000	85	96·7	
18440	65	200·4		18000	71·6	96·8					

MGIPC—M—VIII-3-185—20-4-36—380.

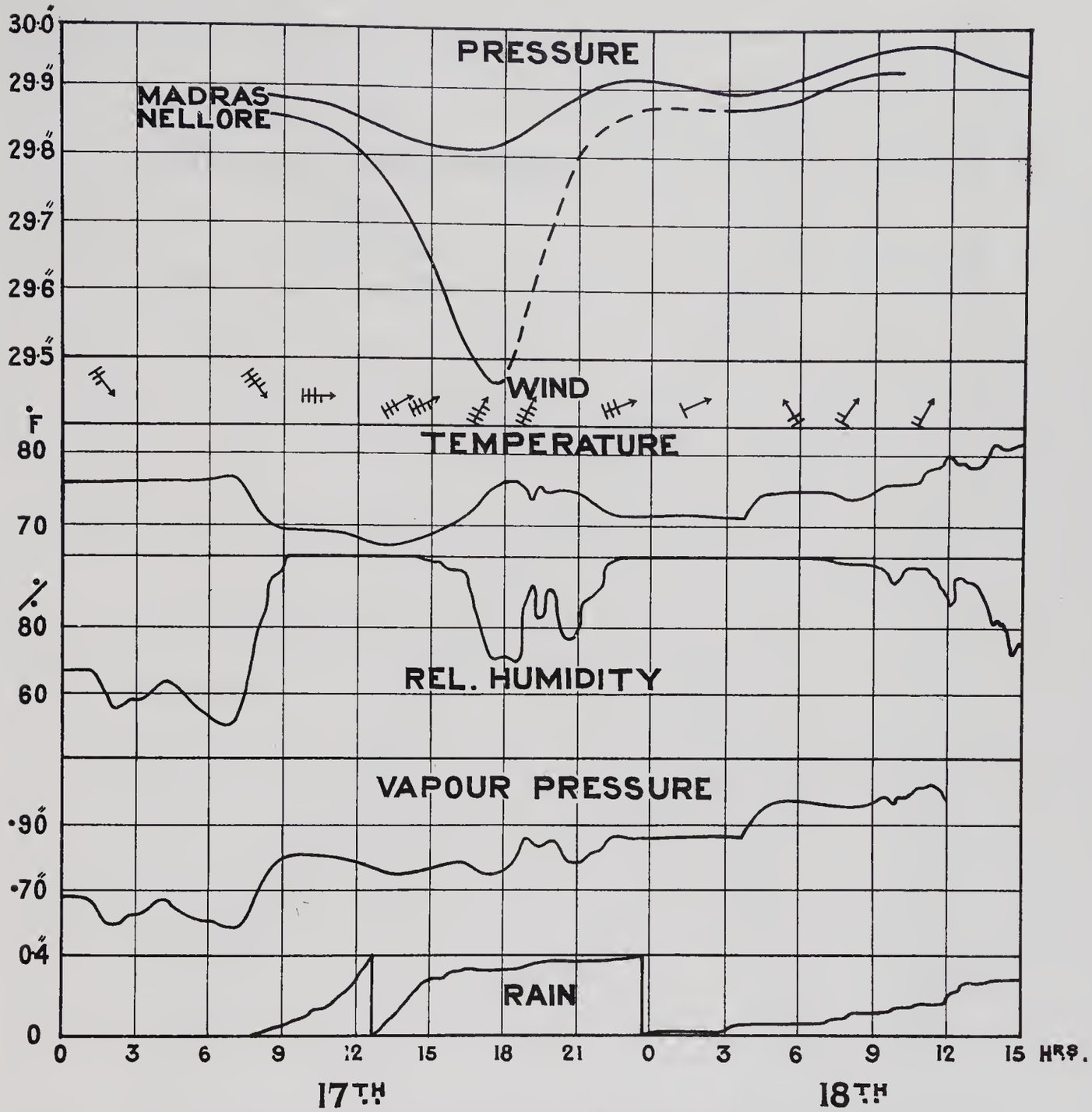
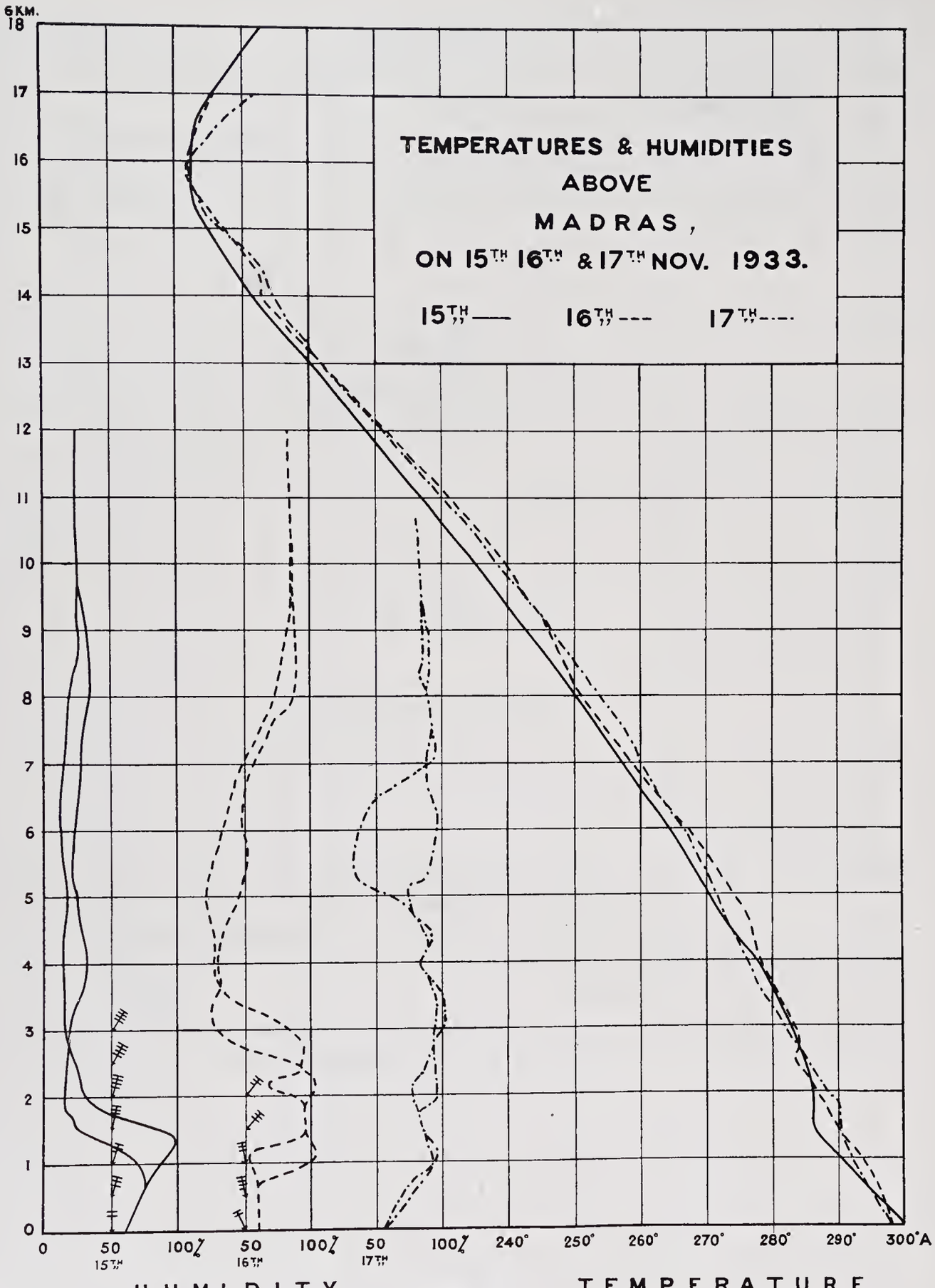


Fig. 3. Variation of the meteorological elements at Madras and pressure at Nellore on the 17th and 18th November, 1933.


6KM.
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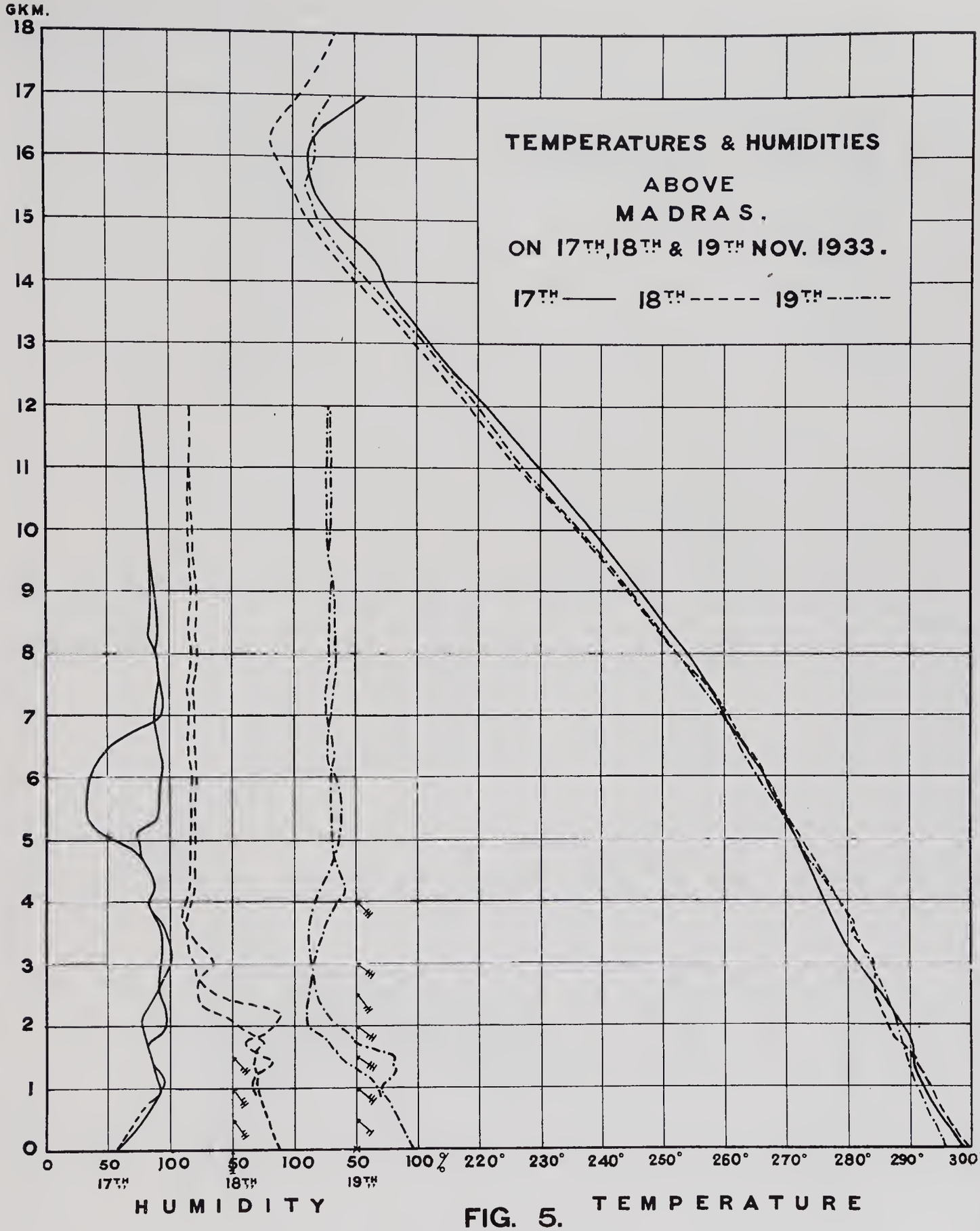
TEMPERATURES & HUMIDITIES
ABOVE
MADRAS,
ON 15TH 16TH & 17TH NOV. 1933.
15TH,, —— 16TH,, --- 17TH,, -·-·
0
50
100%
15TH
50
100%
16TH
50
100%
17TH
240°
250°
260°
270°
280°
290°
300°A
HUMIDITY
TEMPERATURE

FIG. 4.


GKM.
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TEMPERATURES & HUMIDITIES
ABOVE
MADRAS.
ON 17TH, 18TH & 19TH NOV. 1933.
17TH —— 18TH ----- 19TH -·-·-·-
0 50 100 50 100 50 100 %
17TH 18TH 19TH
HUMIDITY
220° 230° 240° 250° 260° 270° 280° 290° 300° A
TEMPERATURE

FIG. 5.

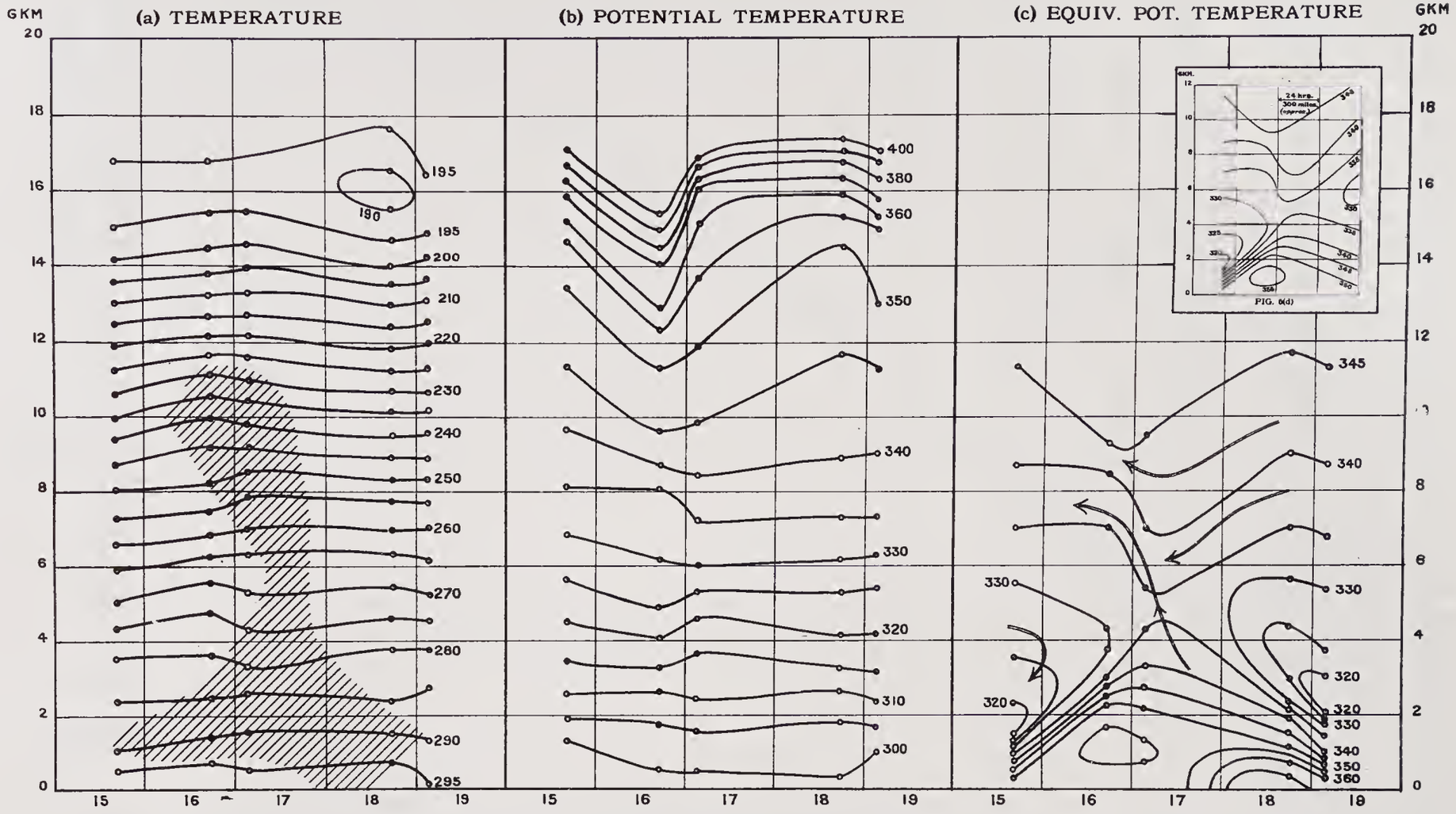
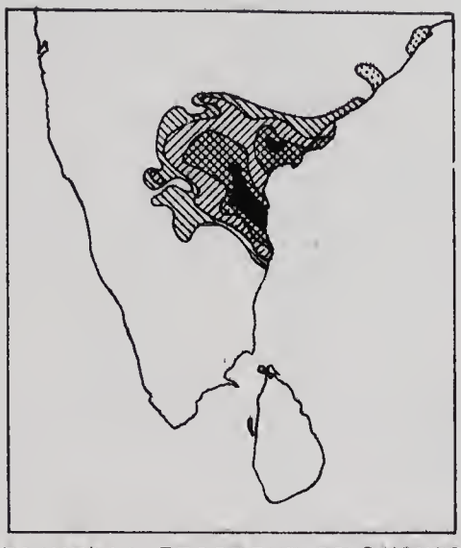


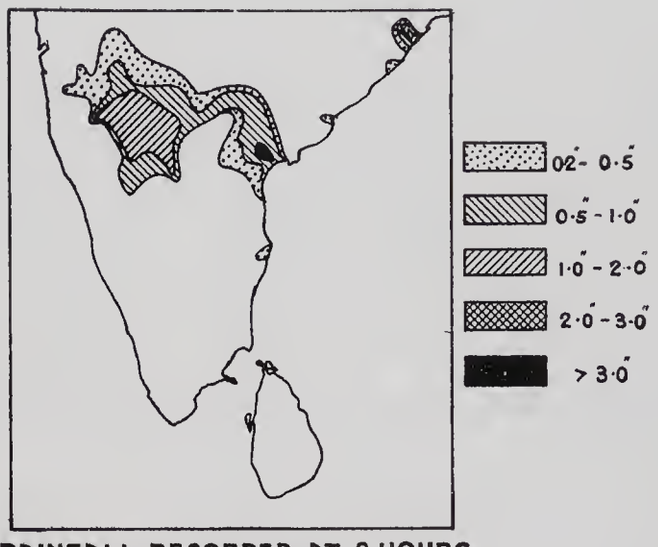
Fig. 6. Isopleths of temperature, potential temperature and equivalent potential temperature drawn from the ascents at Madras.

Inset: Isopleths of eq. pot. temp. modified by partial substitution of Poona data.



RAINFALL RECORDED AT 8 HOURS
ON 18-11-1933.

Fig. 7(a)



RAINFALL RECORDED AT 8 HOURS
ON 19-11-1933.

Fig. 7(b)

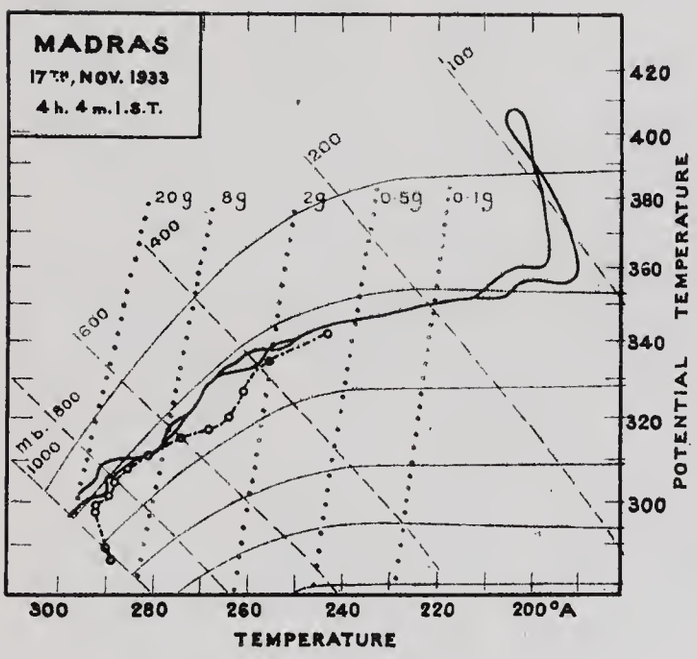


Fig. 11 a

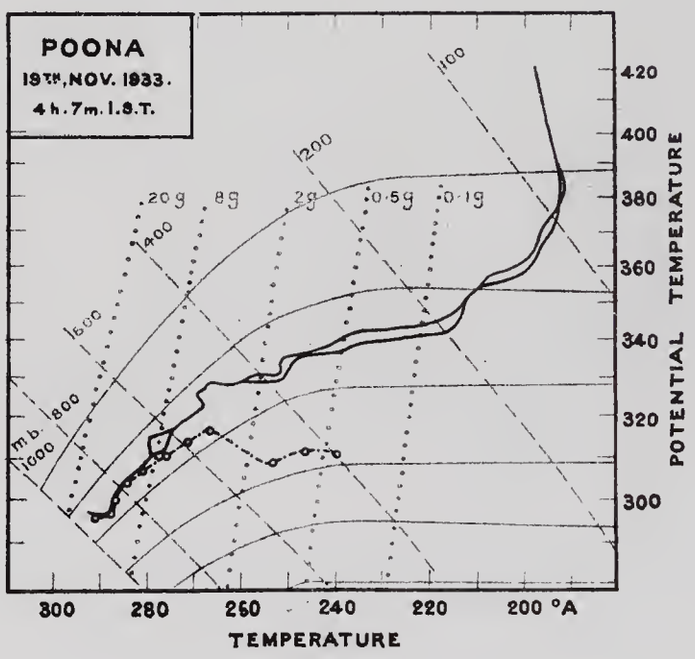


Fig. 11 b

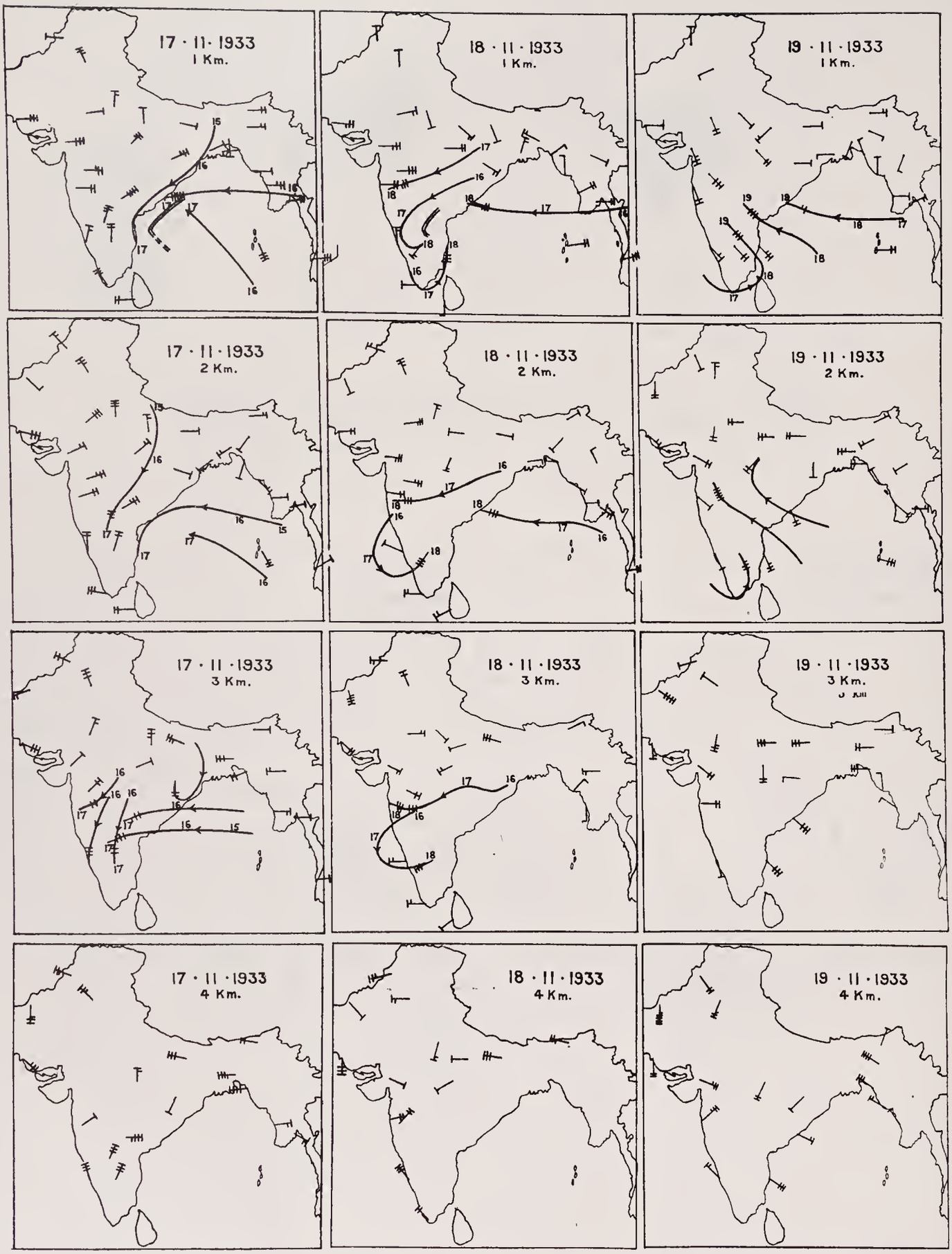
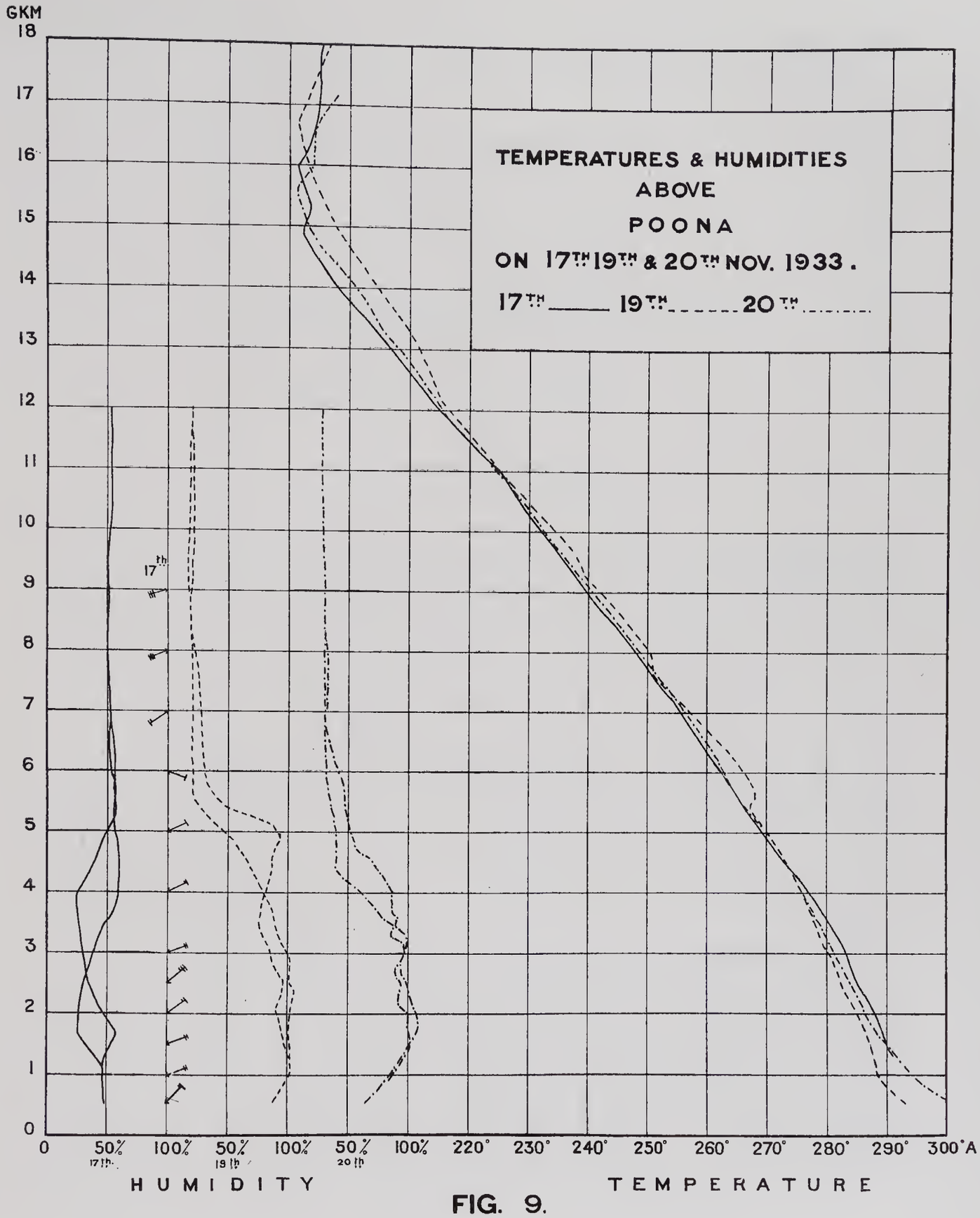


Fig. 8. Upper winds and (selected) trajectories of air movement on 17th. 18th and 19th.


GKM
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TEMPERATURES & HUMIDITIES
ABOVE
POONA
ON 17TH 19TH & 20TH NOV. 1933.
17TH ____ 19TH _ _ _ _ _ 20TH .....
17th
0
50%
100%
50%
100%
50%
100%
17th
18th
20th
HUMIDITY
220°
230°
240°
250°
260°
270°
280°
290°
300°A
TEMPERATURE

FIG. 9.

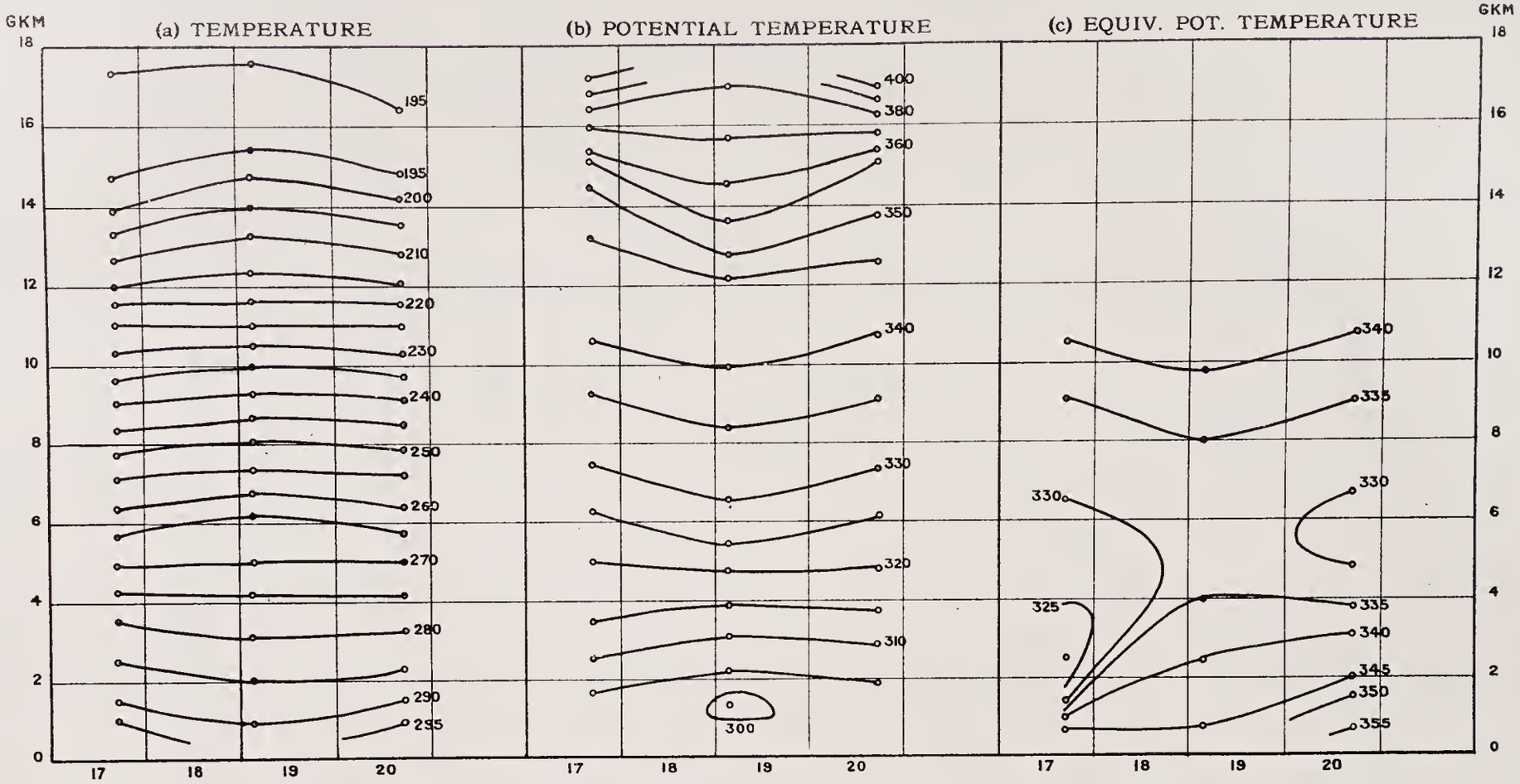

Fig. 10. Isopleths of temperature, potential temperature and equivalent potential temperature drawn from the Poona ascents

MEASUREMENT OF VERTICAL CURRENTS IN THE ATMOSPHERE, MAINLY OF THERMAL ORIGIN, WITH PILOT BALLOONS.

BY

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AND

K. P. RAMAKRISHNAN.

(*Received on 10th April 1935.*)

Summary.—The paper discusses the results of some measurements of vertical currents in the atmosphere obtained with liftless balloons at Poona. These balloons were first carried up to different heights in the atmosphere varying from about 0·5 km. to 2·0 km. and released there by means of timed fuses. On clear days in the dry season, vertical currents are generally weak in the mornings and marked in the afternoons : on one occasion, the upward velocity went up to 14 km./hr. The vertical currents observed on some days with cumulus and cumulo-nimbus clouds are also described.

In the particular ascents discussed in the present note, the vertical currents were mainly thermal in origin and not due to flow of air over obstacles.

Introduction.—It is well-known that vertical currents of considerable intensity and extent are of fairly frequent occurrence in the atmosphere. Measurements of such currents are however few, the main reason for their scarcity being that the vertical velocities are generally small compared to the horizontal velocities of air movement. In Europe, manned balloons and pilot balloons have been used for their investigations[1—4]. In the Forschungs-Institut of the Röhn-Rossitten Gesellschaft[5] which devotes special attention to the scientific study of motorless flying, sail-planes (gliders) have been utilised for studying the vertical currents developed under a wide variety of conditions, such as those associated with wind movement over hilly country, convection over insolated ground, growth of cumulus and cumulo-nimbus clouds and movement of line-squalls. In Britain, the up and down movements caused by eddies in gusty weather have been inferred from the fluctuating readings of acceleromcters carried in aeroplanes.[6] The systematic use of tailed balloons for the measurement of upper winds in India has provided many examples of marked vertical currents but few of them have been published, the only exception being the results obtained at Agra on a day of slightly disturbed weather.[7] In the present note are discussed some experiments carried out at Poona on the measurement of vertical currents in the atmosphere by the use of liftless balloons.

Method used.—The pilot balloons used for investigating the vertical currents were provided with tails of 25 metres length with paper flags attached to them at $6\frac{1}{4}$, $12\frac{1}{2}$ and 25 metres and small bags of sand near the lowest flag. The weight of the sand and the amount of hydrogen in the balloon were so adjusted that the combined system of balloon, tail, flags and sand had no resultant free lift. This system was carried up to the required height by means of another balloon and released there by means of a timed fuse. The sand-bag practically eliminated the slant of the tail, and the flags, in addition to serving as end-marks for the moving base-line, also

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helped to damp out any tendency to pendular motion of the tail. Except when the altitude of the balloon was more than 65°, the angle subtended by the balloon and flags as read in the scale of the eye-piece of the theodolite could be used to determine with fair accuracy the height of the balloon. Readings of azimuth, altitude and tail-length were taken every half-minute. The balloons used were of rubber and either of 90″ or 70″ size, the weight of the sand-bag being usually 50 gms. The no-lift condition was adjusted to within 2 or 3 gms., the small net lift being generally positive. With the particular weight of balloons, load and free lift, a residual free lift of 2 gms. would mean a rate of ascent of about 1·5 km./hr.*

Results.—The balloons were released at different times of the day varying from 8 hrs. to 18 hrs. Notes on some of the successful ascents made on different days are given below. In the tables which follow, the following symbols have been used.

H_o —Height above ground in kilometres at which liftless balloon was detached

H_x, H_n —Maximum and minimum heights reached by liftless balloon.

t—Duration of flight of liftless balloon in minutes.

24TH DECEMBER 1930.—Clear, anticyclonic weather prevailed over Poona on this day and four successful ascents were made.

TABLE I.

Ascents on 24th December 1930.

Time hrs., I. S. T.	H_o (km.)	H_x (km.)	H_n (km.)	t (min.)
1103	0·5	0·7	0·5	10
1234	1·1	1·3	1·1	34
1411	1·25	1·3	0·8	19
1618	1·4	1·8	0·5	49

The height-time curves of the balloons are shown in *Fig. 1.* The

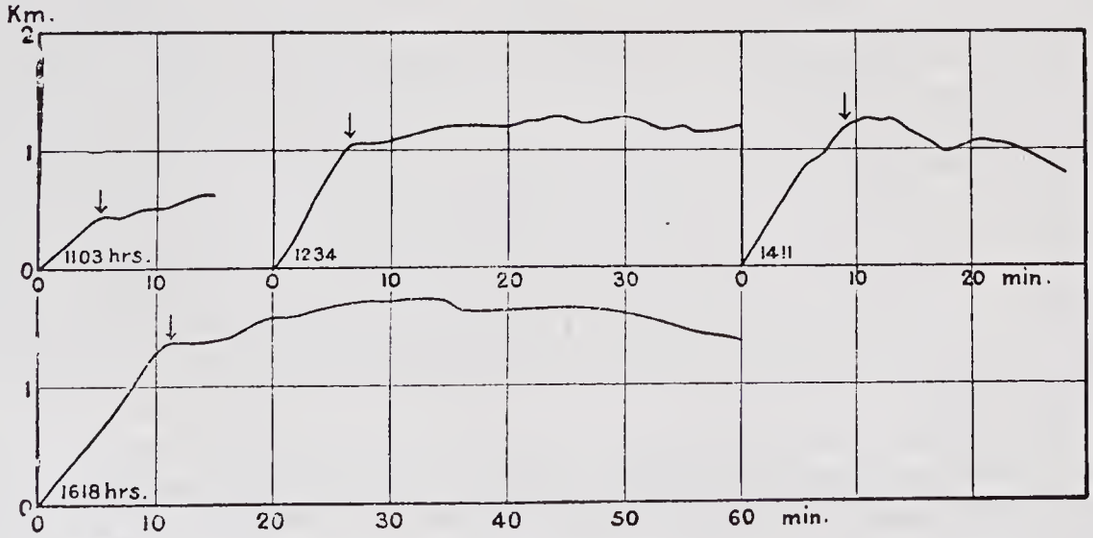

Fig. 1. Height-time curves of some Pilot Balloons sent up on 24th December 1930.

*As there would be a small, slow leakage of gas from the balloon and as the amount of the leakage would vary from balloon to balloon, it was not considered worth while to make a correction on this account.

time at which the liftless balloon was detached is indicated by an arrow. The first ascent shows an abnormally low rate of ascent for the combined system of balloons being only 6 km./hr. against the normal 7·5 km./hr. The second and third ascents show an excess rate of ascent of about 2 km./hr. The ascent at 1411 hrs. shows a downward current of 5 km./hr. lasting for about 5 minutes followed by an upward current. The last ascent shows an upward current lasting for 2-3 minutes. It is probable that the gradual descent of the last balloon which commenced about 50 min. after release was due to leakage of gas. On the whole, the vertical currents were feeble on this day.

20TH JANUARY 1931.—There were eight ascents on this day, details about which are given in *Table 2* below :—

TABLE 2.

Ascents on 20th January 1931.

Time (hrs.)	H_o (km.)-	H_x (km.)	H_n (km.)	t (min.)
0839	0·4	0·4	0·3	7
0921	0·9	0·9	0·8	19
1006	0·8	0·8	0·6	11
1049	2·0	2·1	1·9	44
1216	3·1	3·2	3·1	6
1307	1·9	2·2	0·2	64
1445	0·6	1·7	0·1	100
1652	Liftless balloon not released.			

On this day also, the weather was clear over Poona, although a western disturbance was active in the North-West Frontier Provinces and the Punjab. The trajectories of the balloons sent up between 0839 and 1216 hrs. showed that at those times there was a southeasterly wind up to about 1·3 km. above ground and a westerly wind above. In the afternoon, there were large and irregular changes of horizontal movement probably connected with the mixing of the lower and upper layers of air

In *Fig. 2* are shown the height-time curves of all the balloons sent up on this day and the trajectories of those sent up at 1216 and 1445 hrs. The height-lines of the morning

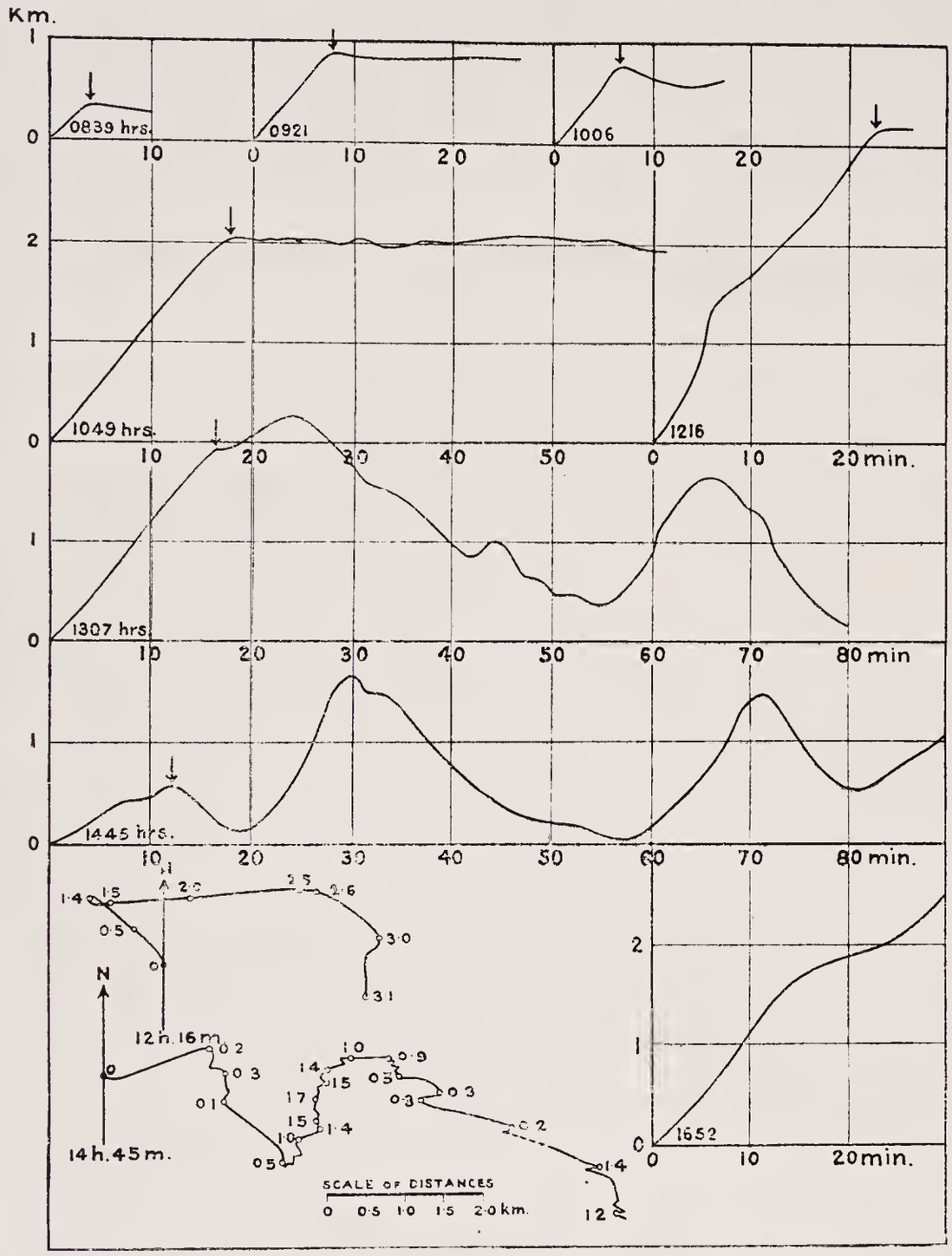

Fig 2. Height-time curves and trajectories of some Pilot Balloons sent up on 20th January 1931.

flights do not show strong vertical currents, but the flight at 1216 hrs. shows abnormally high rate of ascent before the release of the liftless balloon. The two balloons sent up at 1307 and 1445 hrs. show vigorous up and down currents lasting for comparatively long periods of time.

In the second of the above two flights, the mean rate of ascent of the combined system before the release of the liftless balloon was only 3 km./hr. against 7·5 km./hr. which would normally be expected. Upward and downward velocities going up to 14 km./hr. and 9 km./hr. respectively were shown by the latter course of

the liftless balloon. In the flight commencing at 1652 hrs. although the liftless balloon was not released, there are unmistakeable signs of vertical currents.

11TH FEBRUARY 1931.—There was a very weak low pressure area over the east Central Provinces connected with a western disturbance. The weather over Poona was clear. The times and other details of the ascents are tabulated below.

TABLE 3.

Ascents on 11th February 1931.

Time (hrs.)	H_o (km.)	H_x (km.)	H_n (km.)	t (min.)
0827	0·9	1·4	0·9	21
0921	1·2	1·5	1·2	11
1003	Liftless balloon not released.			
1033	1·7	2·3	1·7	12
1123	Liftless balloon not released.			
1301	1·8	2·0	1·8	8
1350	0·8	1·2	0·8	21

The height-time curves and trajectories of all the ascents on this day are given in *Fig. 3.* The trajectories show an interesting change of upper wind during the day. In the morning, there was an easterly current about 0·9 km. deep near the

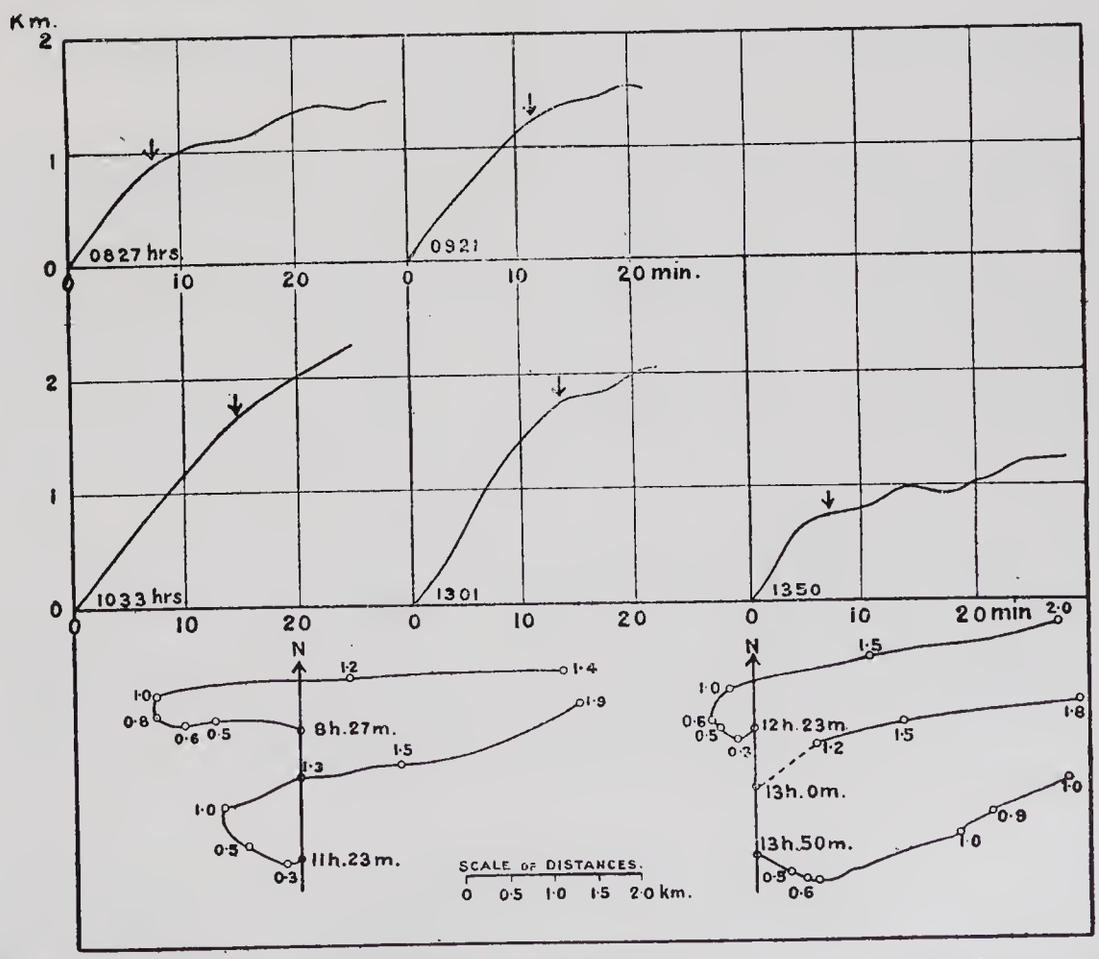

Fig. 3. Height-time curves and trajectories of some Pilot Balloons sent up on 11th February 1931.

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surface with a westerly current above. The former became shallower with the progress of the day and disappeared by 1300 hrs. The height lines of the ascents, which are given in the same figure show that although there were vertical currents, they were rather feeble. The strongest currents were shown by the balloons sent up at 1350 hrs., the vertical velocities going up to only 3 km./hr.

The ascents on this day show that from the mere fact that there exist two superposed streams from different directions, one cannot infer that the vertical currents that may be developed will be intense. The lapse-rates of temperatures in the two layers and the change of temperature taking place at the transition will naturally determine the stability as regards vertical displacements. Unfortunately, no temperature data are avilable to compare conditions on this day with those on 20th January 1931.

29TH MARCH 1933.—There were only two successful ascents on this day, one at 0817 hrs. and the other at 1243 hrs. The liftless balloon was released at 1·0 km. in the first ascent and at 0·6 km. in the second. The first showed only an ascending current with an average strength of 3 km./hr. and the second both ascending and descending currents of about the same average strength.

8TH APRIL 1933.—This was also a clear day, but it was cooler than normal in the central parts of the country, Gujarat and the eastern parts of Bombay Deccan. Information about the ascents is contained in *Table 4.*

TABLE 4.

Ascents on 8th April 1933.

Time (hrs.)	H_o (km.)	H_x (km.)	H_n (km.)	t (min.)
1004	1·2	1·7	1·2	9
1049	1·7	3·0	1·7	20
1242	1·3	2·6	1·3	19
1330	0·4	0·7	0·4	16
1419	1·8	2·4	1·8	20
1507	0·6	0·9	0·3	30
1559	0·8	1·1	0·7	29

The height-time curves of the balloons are shown in *Fig. 4*. Perhaps owing to

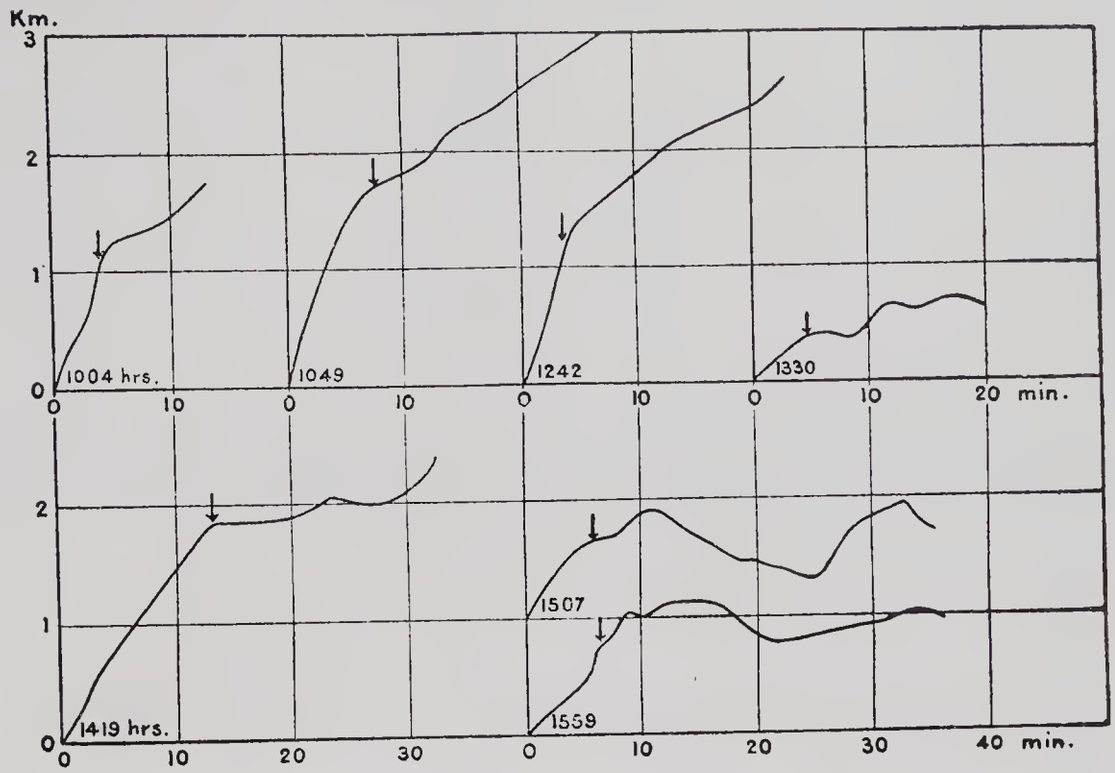

Fig. 4. Height-time curves of some Pilot Balloons sent up on 8th April 1933.

the extra instability due to the coolness of the upper air, the rates of ascent were exceptionally high in the first three ascents before the release of the liftless balloons and there were also strong upward movements of the liftless balloons. One is tempted to suspect that there was some error in free lift, but the original records do not show any special reason for suspicion. Assuming that there was no error in the measurement, the intensity of the ascending currents were from 4 to 10 km./hr. The afternoon ascents show both ascending and descending currents. For example, the flight commencing at 1507 hrs. shows descending currents of 2-6 km./hr. and ascending currents going up to 6 km./hr.

10TH APRIL 1933.—There were only two ascents on this day; both were made in the afternoon at a time when there was growing cumulus. The first ascent commenced at 1533 hrs. and the second at 1637 hrs. Thunder was heard between 1615 and 1725 hrs. It is interesting to note that in the second ascent, there was sustained upward current from the ground up to 3·3 km., the average upward velocity being about 4 km./hr. and the maximum velocity about 7 km./hr.

9TH OCTOBER 1934.—There was an extensive, diffuse low pressure area lying over the whole of the Bay of Bengal and part of the Deccan. On the afternoon of this day, there were thunderstorms at Poona and its neighbourhood; rain fell at Poona between 1552 and 1600 hrs. Twelve special ascents were made on this day, particulars of eight of which are given in *Table 5*.

TABLE 5.

Ascents on 9th October 1934.

Time (hrs.)	H_o (km.)	H_x (km.)	H_n (km.)	t (min.)
0930	1·1	1·1	0·2	9
0941	2·6	3·2	2·6	16
1015	1·1	2·0	1·1	23
1105	1·3	1·3	1·2	4
1245	2·3	2·8	2·2	11
1325	0·7	1·7	0·7	25
1408	1·6	1·7	1·6	0
1516	0·5	1·7	0·5	33

The height-time curves of all the ascents and the trajectories of three of them are shown in *Fig. 5*. The ascent at 1245 hrs. showed a large upward current of nearly

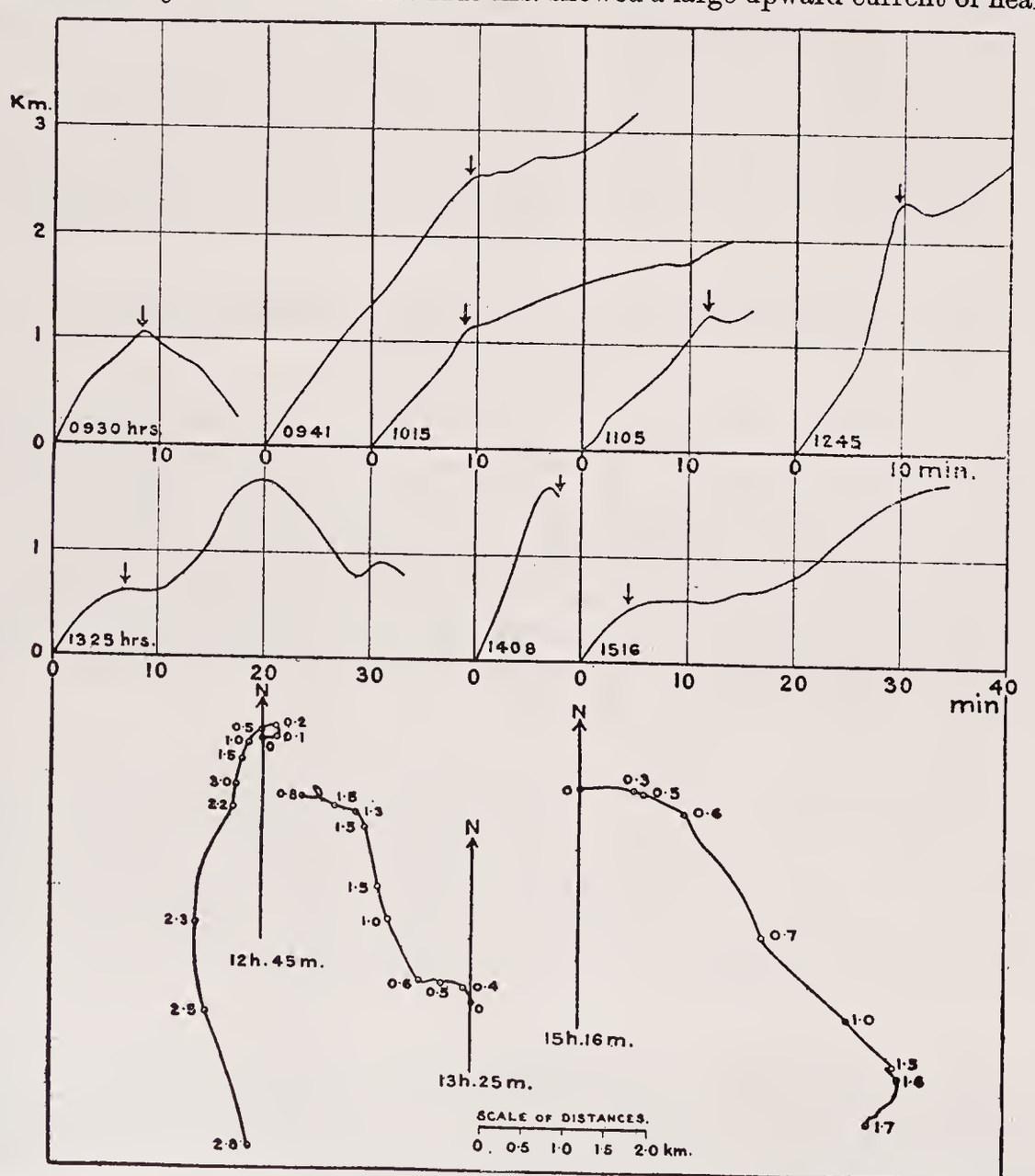

Fig. 5. Height-time curves and trajectories of some Pilot Balloons sent up on 9th October 1934.

16 km./hr.* before the release of the liftless balloon. Both upward and downward currents were shown by other ascents also, the one sent up at 1325 hrs. indicating up and down currents of about 8 km./hr. It is interesting to note that there were considerable differences between the trajectories of the balloons sent up at 1245, 1325 hrs. and 1516 hrs. the first one showing a northerly, the second a southerly and the third a northwesterly wind between 0·5 and 1·5 km. The autographic charts of wind and temperature, which are reproduced in *Fig. 6* (*Plate I*), show weak winds with fluctuating direction till 1525 hrs. and moderately strong westerly to west-northwesterly wind later. The fall of dry bulb and rise of wet bulb temperature a little before the onset of the westerly wind is noteworthy. It suggests that the westerly wind was of the nature of a sea-breeze[8]. Rain commenced about half an hour after the beginning of the westerly wind.

12TH OCTOBER 1934.—On this day, the low pressure area in the Bay was concentrating into a depression. Thundershowers occurred extensively in the Deccan. There were cumulus and cumulonimbus clouds at Poona and four special ascents were made, all in the afternoon, particulars of which are given in *Table 6.*

TABLE 6.

Ascents on 12th October 1934.

Time, (hrs.)	H_0 (km.)	H_x (km.)	H_n (km.)	t (min.)
1318	1·6	2·0	1·6	8
1343	1·4	2·0	1·4	10
1421	0·6	1·7	0·6	16
1540	0·8	1·2	0·8	4

The height-lines and trajectories of these are reproduced in *Fig. 7.* There

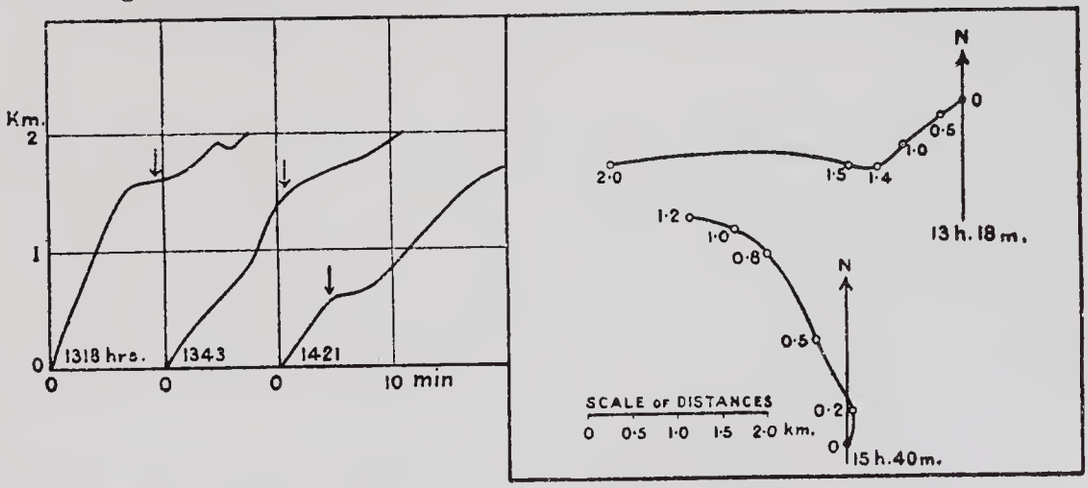

Fig 7. Height time curves and trajectories of some Pilot Balloons up on 12th October 1934.

was a shower between 1445 and 1455 hrs. and another between 1550 and 1620 hrs. Vertical currents going up to 7 km./hr. are noticeable in all the height-lines. The trajectories show that a northeasterly current at 1421 hrs.† was replaced by a southeasterly at 1540 hrs. The autographic charts from Poona are reproduced in *Fig. 8* (*Plate II*).

*To obtain this, the normal rate of ascent calculated from the net free lift and weight was assumed.

†Traiectory not reproduced.

Discussion.—The trajectories of the ascents of the no-lift balloons were examined with reference to the contour of the surrounding country to see if the vertical currents could be associated with topographical features. No definite connection could be established and it may therefore be taken that the currents revealed by these particular ascents were mainly due to thermal turbulence. It should be remembered that the releases of the no-lift balloons generally took place at heights varying from 0·5 to 2 km. above ground, while the variations of ground-level in the region of travel of the balloons were not more than 0.2 km.

The strength of the up and down currents recorded above may be compared with some of those observed in Europe. German workers, using liftless pilot balloons released from aeroplanes have observed vertical currents going up to 10 km./hr. (2·8 mps.) on a hot afternoon. An upward wind of nearly 12 km./hr. (3·2 mps.) was experienced at a böenfront by Kronfeld flying in his sail-plane 'Wien' between the heights of 950 and 1600 metres. Still stronger were the currents encountered by Bedau in a towering cumulus in which the vertical velocity went up to more than 21 km./hr. (6 mps.). The readings obtained in England with accelerometers carried in aeroplanes flying in gusty weather showed vertical currents whose most frequent velocities lay between 2 and 5 km./hr. but occasionally went up to 18 km./hr. (17 ft./sec.) in cumulus clouds.

Recently, regular flights of pilot balloons with extra ballast to reduce the slant of the tail have been made at Poona and these show that measurable vertical currents are noticeable in the first two kilometers on more than 50% of the sunny days between 10 hrs. in the morning and sunset. Even on clear days, their magnitude may be as much as on cumulus days. The maximum upward velocity that has been observed with pilot balloons is 15 km./hr. in heavy cumulus weather. There have however, been other occasions, especially during thunderstorms, when sounding balloons having a normal rate of ascent of about 16 km./hr. have been carried down from heights of about 10 km. to 2 or 3 km. and again been carried up. These facts show that the intensity of the vertical currents experienced in India are about the same as those met with in Europe, but it is probable that they often extend to greater heights.

Gliders of modern design have rates of descent as low as 2 to 3 km./hr. and it is clear that on most sunny days in the Deccan (and presumably in other parts of the country as well) the thermal currents that are developed after 10 o'clock would be capable of sustaining soaring flight of gliders for a few hours at a time.

All the members of the staff of the Upper Air Section have taken part in this work in some way or other, and our best thanks are due to them for their hearty co-operation.

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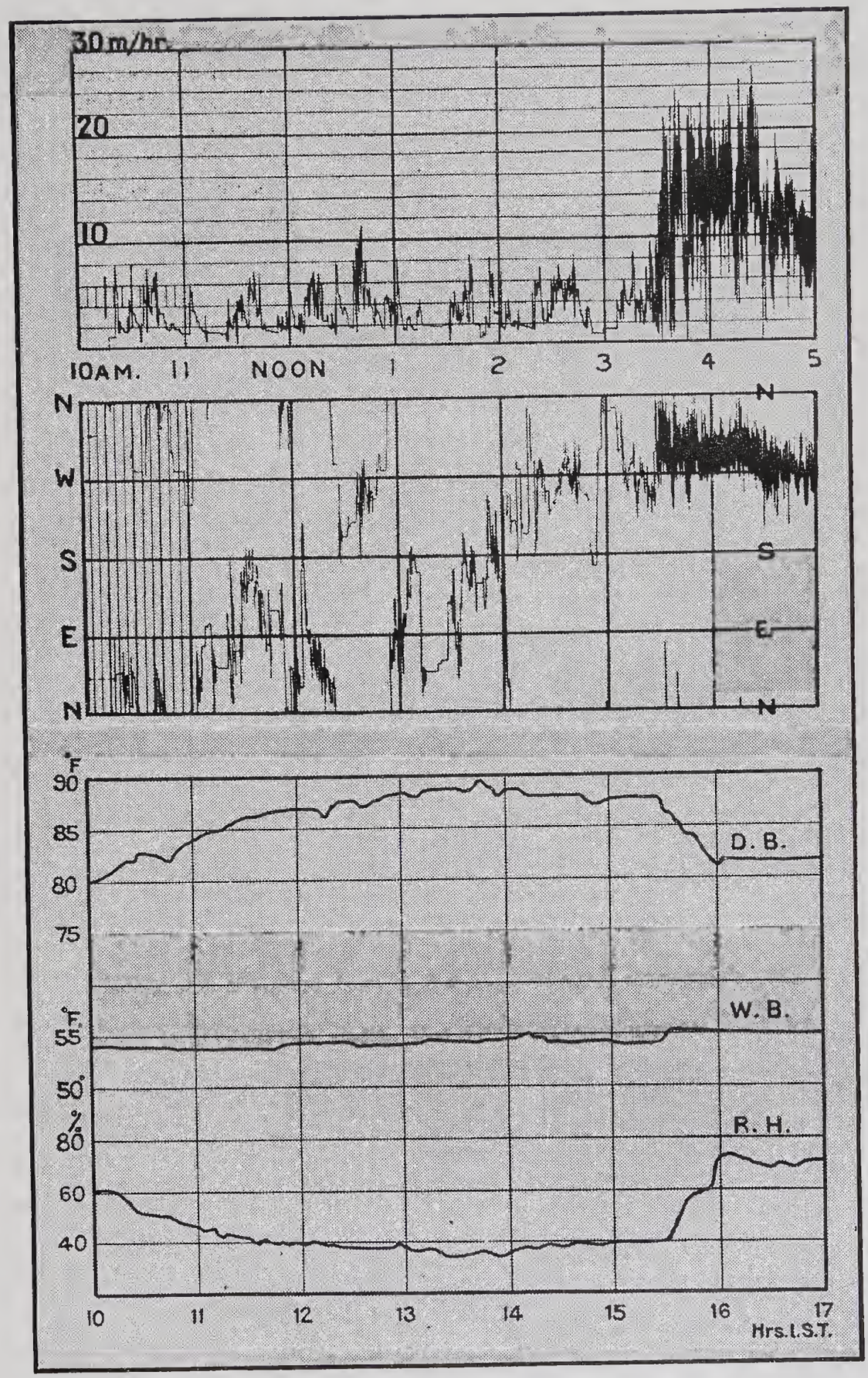

FIG. 6 WEATHER AT POONA ON 9-10-1934.

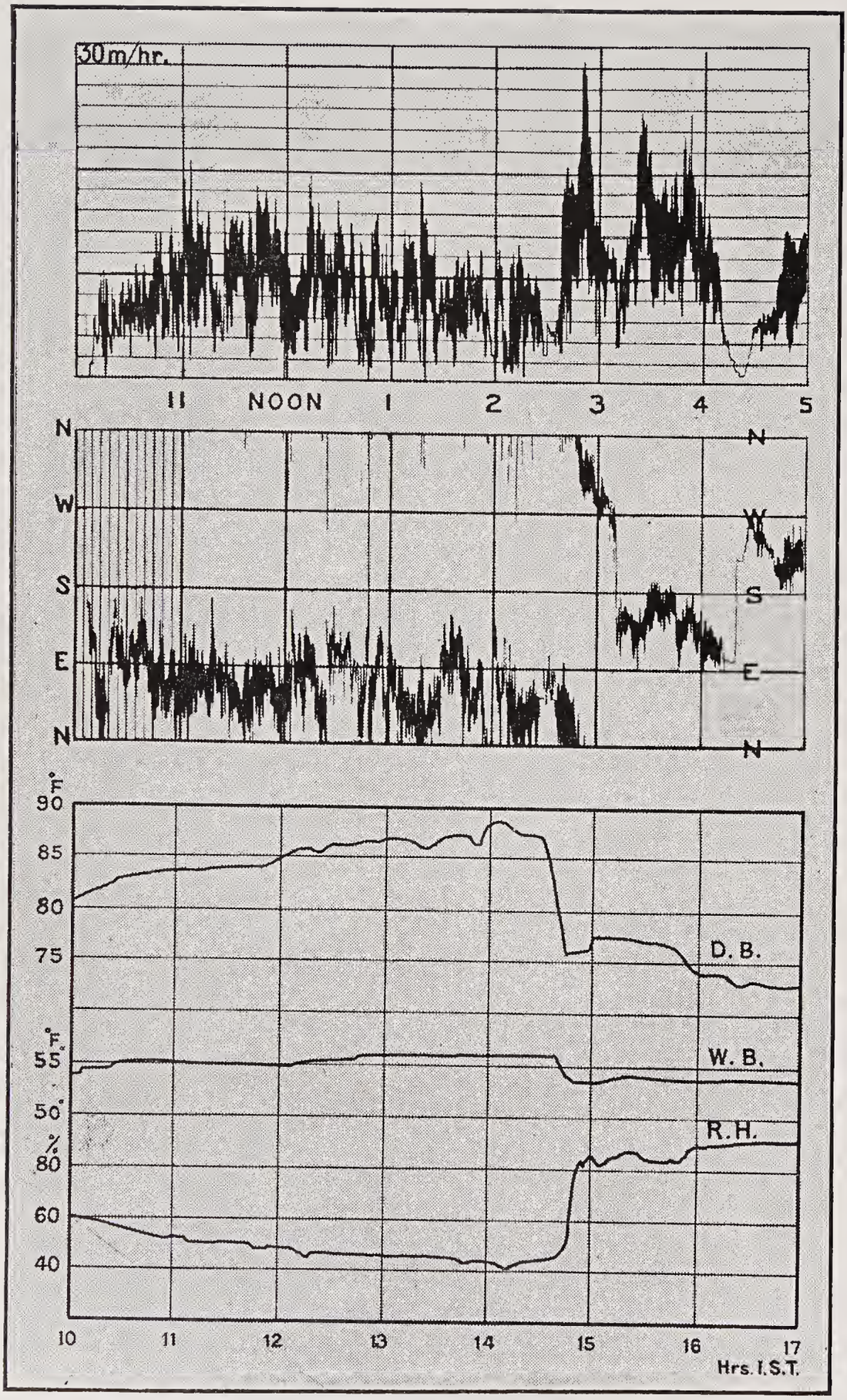

FIG. 8. WEATHER AT POONA ON 12-10-1934.

Exploration of the Upper Atmosphere by means of Sound Waves.

By K. R. Ramanathan,
Indian Meteorological Department, Poona.

THE maximum height which balloons carrying self-registering instruments have reached is about 35 km. A limit to the attainable height is set by the properties of the fabrics out of which balloons can be made. With improved fabrics it is possible that this height may be exceeded, but this is a problem for the future. An altogether different method for studying the physical conditions in the layers of the atmosphere which lie immediately above the reach of balloons is by the use of sound-waves. Beginning from 1904, when Van d. Borne discussed the propagation of sound-waves proceeding from an explosion of dynamite in Westphalia, the subject has developed considerably. During the second Polar Year, August 1932 to August 1933, a special series of explosions were arranged in Holland and also in the Polar regions. The results of this and other previous work are collected together in a special number of the *Zeitschrift für Geophysik* published last year. A lucid resumé of the present position of the subject and an account of the work done in England in the last decade is contained in the Symons Memorial Lecture delivered in March 1935 before the Royal Meteorological Society of London by Dr. F. J. W. Whipple, the Director of the Kew Observatory, and the foremost worker on the subject in Britain.

Some of the principal features of the propagation of sound from a loud explosion which can be inferred from aural observations can be summarised as below. Surrounding the source of sound, there is a region of 50–60 km. radius in which the intensity of the sound falls off gradually with distance; beyond 50–60 km. the sound is not audible. Going farther from the source, the sound again revives, often sharply, at a distance which may vary from 100 to 200 km. This second "zone" of audibility is often about 100 km. wide. If we calculate the velocity of the sound heard in this region from the distance from the source and the time between the explosion and the time of hearing the report, the computed velocity is found to be much smaller than the velocity corresponding to the temperature prevailing in the lower atmosphere. An explanation of these peculiarities was offered by Van d. Borne himself. In the immediate neighbourhood of the source the sound travels in the lower atmosphere, but that received in the second zone comes not directly, but by a longer path after reflection from the upper atmosphere. Timing the reception of the sound at known distances enables the determination of the delay in making the detour and the results of observations show that the sound gets reflected at heights ranging from 35 to 45 km. in the atmosphere.

Curr. Sci. 4, 140–142, 1935–36.

Occasionally, the second zone of audibility is followed by yet a third one with a second zone of silence between. The sound received in this zone is due to waves reflected twice from the upper atmosphere and once from the ground.

The hearing of gun-fire at great distances from the battle-front during the European War in 1914–18 provided much interesting new information. It was found that during summer in Europe sounds travelled to great distances to the west, while during winter, they could be heard much farther in the east. The audibility at the same distance in different directions was not also the same. Further progress in the subject came with the organisation of pre-arranged explosions and the development of the technique for the reception of the sound. In the Continent of Europe, special explosions were made by the destruction of surplus munitions and in England advantage was taken of the firing of artillery guns. The receiving instruments used in Germany are based on the principle of magnifying optically the movements of a light piston or stretched membrane at the mouth of a resonator; in England, Tucker's hot-wire microphone is used. The arrival of waves is recorded at a number of places at distances going up to 300 or 400 km. from the source and advantage is taken of the broadcasting organisation to send wireless waves every second for time-marking purposes. An important quantity that is determined in recent work is the angle which the arriving wave makes with the horizontal; this gives the velocity of sound at the topmost part of the trajectory, being equal to $v \sec i$, where v is the velocity of sound near the ground and i the angle which the trajectory makes with the ground. The angle generally lies between 10° and 35°. Knowing the velocity of propagation at the topmost part of the trajectory and the distribution of temperature in the first 30 km., it is possible with certain simple assumptions to complete the trajectories of the sound in the upper atmosphere. The assumptions usually made are that up to a certain height, the velocity of sound in the stratosphere is constant and that above this it increases rapidly. In recent calculations, the influence of wind in the accessible layers of the atmosphere is also taken into account. The calculations show that the downward movement of sound begins at 35–45 km. The increased velocity in the upper atmosphere implies either an increase of temperature or a decrease of molecular weight. For various reasons, the former alternative is believed to be true in the layers under consideration.

The average distribution of temperature in the upper atmosphere over Europe in summer deduced from the collected results of these experiments is shown in Fig. 1.

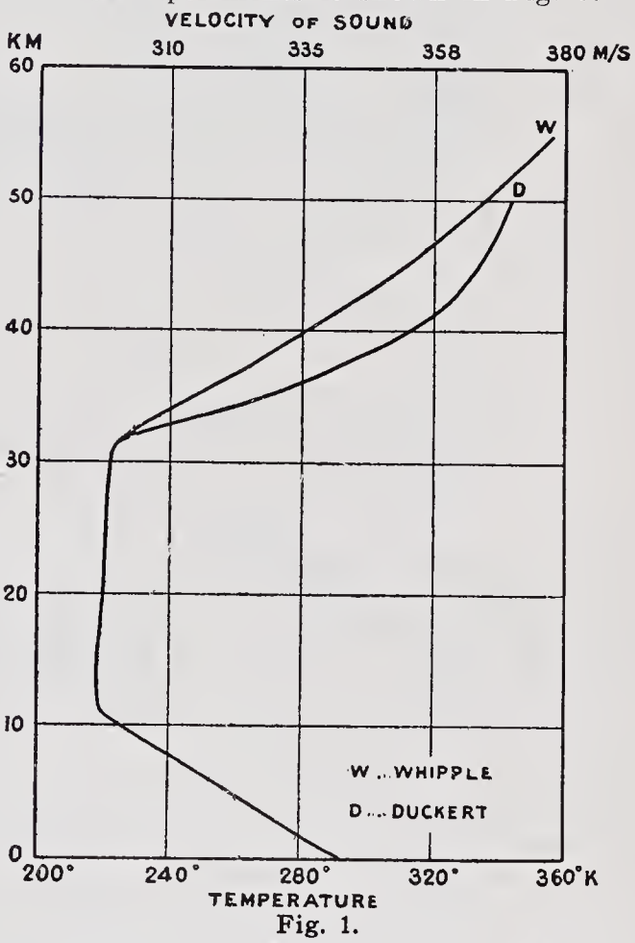

Fig. 1.

The marked difference between summer and winter as regards audibility at stations east and west of the source has already been mentioned. The records of self-registering instruments also show differences of times of travel of sound in different directions which can only be explained by large velocities of the order of 20–40 metres per second in the stratosphere, easterly in summer and westerly in winter. Many other facts such as the movement of persistent meteor trails and luminous night clouds support the same conclusion.

A reason for the strong westerly and easterly winds in winter and summer respectively in European latitudes has been put forward by Whipple. The results of sounding balloon ascents made at Abisko in Lapland during the years 1921 and 1929 showed a remarkable annual variation of

temperature in the stratosphere, the mean temperature at 18 km. changing from 235° A. in June and July to about 210° A. in November to February. This very large change of temperature causes a seasonal change of pressure gradient between the temperate and polar regions causing easterly winds in the stratosphere in summer and westerly winds in winter.

The rise of temperature above 35 km. in the temperate latitudes is generally attributed to the absorption of ultra-violet solar radiation by ozone in the region 2,900–2,200 A.U. Taking the distribution of ozone in the vertical as worked out by Dobson, Götz, and Meetham, and assuming that the main radiating substance in the stratosphere below 50 km. is water-vapour (in such quantities as we may reasonably expect to be present) and carbon dioxide, it is easy to explain the course of temperatures over Europe deduced from experiments on the propagation of sound from explosions. But the fact that even in Polar regions in winter where the atmosphere has not received solar radiation for weeks, the phenomenon of anomalous propagation of sound is observed shows that the above explanation is insufficient.

Observations of the anomalous propagation of sound in the tropical atmosphere are practically absent, the only known instance in low latitudes being those of an explosion of a train-load of gelignite in South Africa in July 1932, when the sound was heard at a distance of 500 km.

It is obvious that the detailed investigation of the propagation of sound to great distances in low latitudes cannot fail to yield results of fundamental importance to the Physics of the Atmosphere. If the sympathetic co-operation of the Indian Military Department can be secured, the problem does not appear to present serious difficulties. Side by side with this, the problem of the vertical distribution of ozone in our latitudes would also have to be investigated.

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THE GENERAL CIRCULATION OF THE ATMOSPHERE OVER INDIA AND ITS NEIGHBOURHOOD.

By

K. R. Ramanathan and K. P. Ramakrishnan.

(Received 21st December 1937).

Summary.—The paper gives charts of mean air movement in each month over the Indian region at different heights up to 8 km derived from observations of pilot balloons at the observatories of the India Meteorological Department. As complementary to the charts of pilot balloon winds, which refer mainly to days of clear weather, charts of movement of low, medium and high clouds are also given for five months. Upper air temperatures deduced from the change of wind with height are also shown on the charts. The charts for the lower levels contain as insets wind-roses for selected stations.

The chief features of the upper wind and temperature distribution in each month are described and their relation to the major climatological features such as monsoons and storms are pointed out. Some of the points discussed are :—

(i) the boundaries between easterly and westerly winds in different months of the year,
(ii) the influence of the Himalayas and adjacent mountain ranges on the circulation,
(iii) the increase of temperature in the upper levels over regions of heavy rainfall, and
(iv) the greater northward movement of air in cloudy weather than in clear weather.

Tables of resultant and predominant winds as well as frequencies of directions of cloud movement are appended.

Introduction.

A discussion of the upper air movement in the Indian monsoons and its relation to the general circulation of the atmosphere was made in 1921 by Harwood[1]. Since then, much new knowledge of the upper atmosphere in India both as regards winds and thermal conditions has accumulated, and particular aspects of the question of atmospheric circulation have been considered in a few departmental publications.[2 to 5] An important contribution has also come from Wagner.[6] In the present paper, a more complete survey of the whole problem is attempted with special reference to the gradual development of conditions from month to month. For the purpose of this discussion, charts of monthly mean stream-lines have been prepared from pilot balloon data for the levels 1, 2, 3, 4, 6 and 8 km. These have been supplemented by charts of frequencies of wind at different levels, of frequencies of direction of movement of low, medium and high clouds and of upper air isotherms which have been computed from the variation of pilot balloon winds with height.

Monthly mean stream-line charts.

The monthly mean resultant winds at a number of levels over each pilot balloon station under the India Meteorological Department are published annually. The resultant winds in each month used in preparing the wind charts given here are the means of all the morning observations till the end of 1931 or 1934. Data up to the end of 1931 only

Mem. Ind. Met. Dept. 26(10), 189–245, 1939.

have been used for the older stations ; for those started in 1926 or after, data up to the end of 1934 have been used. The resultant monthly directions (D) and velocities (v) and the average speeds irrespective of direction (V) together with the number of observations (n) at each level are tabulated in *Appendix A*.* The relative values of V and v convey an idea of the variability of wind, small values of v/V implying great variability and values approaching 1 implying great steadiness. The directions of the resultant monthly winds at the different pilot balloon stations have been plotted as arrows, the number of feathers on each arrow representing the strength of the wind on the Beaufort scale. Stream-lines have been drawn on the charts, but no attempt has been made to space them quantitatively.

In the charts for 1, 2 and 3 km, wind-roses at some selected stations have also been given as insets.

Frequencies of cloud directions.

Pilot balloon data, by themselves, can give only a partial view of atmospheric circulation as the data would necessarily be lacking at a number of levels on days of clouding. The deficiency will be greater, the higher the level considered. At many stations, in some months of the year, the pilot balloon data will therefore be unrepresentative of mean conditions ; this can to some extent be corrected by considering the directions of cloud movements. Even then, on days with a large amount of low cloud, observations of middle or high clouds will generally be unavailable.

Monthly percentage frequencies of movement of low, medium and high clouds at all the pilot balloon stations of the India Meteorological Department and at Bombay, Jaipur, Kodaikanal, Madras and Trivandrum have been published for the years 1926-35 in the ' Annual Summaries ' or in the ' Upper Air Data, Part 13.' From the above data, the average percentage frequencies of cloud movement for each month and for a large majority of the stations were worked out and plotted on charts. Tables of average frequencies of direction of cloud movement are given in *Appendix B*. These average frequencies are obtained by averaging the percentages in the different years ; no account has been taken of the difference in the number of observations from year to year. In this respect, the process of averaging differs from that adopted for pilot balloon winds where each observation (and not each year's average) was equally weighted. Charts of cloud movement have been added as insets in the stream-line charts of January, April, July, October and November—the charts of low cloud in 2 km, of middle cloud in 4 km and of high clouds in 8 km charts.†

Isotherms in the upper atmosphere.

The variation of wind with height has been previously made use of to a limited extent for the calculation of horizontal temperature gradients[7], [8]. This calculation is based on the assumption that, at each level, the geostrophic wind equation holds and that the variation of wind with height is due to a variation of pressure gradient which itself must be brought about by a horizontal temperature gradient in the intervening layer.

* Data for 0·5 km above sea are also given in *Appendix A* ; but charts have not been prepared for 0·5 km.

† The cloud charts for all the months except November are based on data for one or two years fewer than those given in *Appendix B* ; this fact, however, does not affect the main features shown by the charts.

The frequencies of cloud directions are based on observations at 8, 12 and 16 hrs. till the end of 1931 and at 8 and 16 hrs. only in later years.

The procedure adopted for drawing the isotherms was as follows :—

For each station, from the normal values of north and east components of wind at two neighbouring levels, for example at 1 and 2 km, the east and north components of the horizontal temperature gradient (in °C per 100 km) for the layer 1-2 km was calculated by using the equations—

$$\frac{d}{dz}\left(\frac{u}{T}\right) = \frac{g}{2\,\omega \sin \varphi} \quad \frac{1}{T^2} \quad \frac{dT}{dy}$$

$$\frac{d}{dz}\left(\frac{v}{T}\right) = \frac{g}{2\,\omega \sin \varphi} \quad \frac{1}{T^2} \quad \frac{dT}{dx}$$

where u and v are the components of wind velocity along the x and y axes (east and north) respectively and the other symbols have their usual meanings.[9, 10]

It will be seen that T occurs in the equations, but approximate values of it are sufficient for this purpose, as small differences in the values employed will not affect the computed values of dT/dx and dT/dy to the order of accuracy otherwise attainable. The normal values of temperature obtained from sounding balloon ascents at Agra were used for stations in north India and those obtained at Poona or Hyderabad for stations in the south. The gradient calculated from the change of wind from one level to the next was taken to apply for a level midway between the two. Thus the gradient calculated from 1 and 2 km winds was taken as relating to 1·5 km, that calculated from 4 and 6 km winds to 5 km and so on.

The gradients in two perpendicular directions thus obtained were combined into a single vector and these vectors for all the stations charted. The chart for January for the layer 1-2 km (*i.e.*, for the level 1·5 km) is shown in *Fig. 1* as an example. Isotherms were then drawn on this chart remembering that (i) the isotherms should everywhere cut the gradient vectors at right angles and (ii) the spacing of successive isotherms should accord with the magnitudes of the gradient vectors. The actual values of temperature for these lines were then based on the mean temperatures at Agra[11] and Poona (or Hyderabad)[12] and to some extent on those at Peshawar or Quetta.[13] In general, the differences between Agra and Poona agreed well with the gradients between the stations. From the charts of 1·5 km, 2·5 km, etc., the vertical lapse-rates of temperature for each station were tabulated and, combining these with the temperatures at these levels, the temperatures at the standard levels, namely 1, 2, 3, 4 and 6 km, were calculated. These were plotted on charts and smoothed isotherms drawn. On individual days, with a changing system of isobars, it would not be permissible to assume steady-state conditions to calculate pressure and temperature gradients. Even when we are considering the mean conditions over a place and the data are based on a large number of observations under different weather conditions, the method cannot be expected to give accurate absolute values of temperature in different parts of the country nor give definite information about inversions, but nevertheless, they will give a broad indication of the general temperature distribution in the atmosphere both in the horizontal and vertical directions.

The isotherms have been shown in the stream-line charts themselves in broken lines. The temperature values are in degrees absolute, with the hundreds figures omitted. The combined charts of stream-lines and isotherms have been found to be illuminating regarding the properties of air coming over a place at different levels.

Main features of upper wind and temperature distribution in the different months.

JANUARY.

Considering the area as a whole, winter conditions are most marked in this month. Tropical storms are very rare in the neighbouring seas and, when they do occur, they are of moderate or slight intensity, affect only the extreme south of the area, generally south of lat. 13°N. and move in a westerly to northwesterly direction. Disturbances of the temperate latitude type, and often occluded, traverse north India with more or less regularity from west to east. The effect of these disturbances is greatest in Kashmir and the hills of the north and east Punjab.

Upper Winds.

1 km.—The circulation at 1 km is very similar to that at the surface.[14] The main features are :—

(i) The slow drain of cold air from Persia and Baluchistan towards the neighbouring seas and from and along the Himalayas towards the head of the Bay of Bengal. Note the flow of air down the Brahmaputra valley towards north Bengal and the extremely weak wind at Rangpur. Along the Mekran Coast, weak easterly winds (SE, E and NE) are frequent at 0·5 and 1 km above sea level.

(ii) The curving of the north Indian air round the anticyclonic region which extends from Gujarat to Orissa. The anticyclone is more intense over land than over the neighbouring seas.

(iii) The presence of an easterly current in the south of the Bay and of the Peninsula. In the middle of the Peninsula, the easterly stream is mainly anticyclonic continental air, while, as we go farther south, the air although of continental origin has passed for longer and longer distances over the sea. The air which enters the Bay of Bengal from the north or east and moves towards the south of the Peninsula will pick up moisture on its way and being less subject to nocturnal radiation cooling near the ground, will progressively gain in latent instability. Even in the south of the Bay, the air which crosses over to the Bay from the eastern side of Tenasserim is on most occasions continental air which has travelled round the anticyclone in Siam and Cochin China.

The mean velocities at 1 km in most parts of the area are of the order of 2 m/s. Velocities of over 4 m/s occur in the lower end of the Gangetic Valley, in the south of the Peninsula east of the Ghats and in the south of the Bay.

2 km.—At 2 km the effects of local radiational cooling are less marked, but the control exercised by the high mountain system in the north of the country remains strong. Note for example the weakness of wind at Quetta, Lahore, Peshawar, and Tezpur and the large wind-velocities (exceeding 8 m/s) in the Gangetic valley, in the United Provinces, Bihar and Bengal. The anticyclone is still stronger over land than over the neighbouring sea but the flow of air from the north of the Central Indian anticyclone to its south is less pronounced than at 1 km.

3 km.—At 3 km, the influence of the lower ranges of mountains such as the Sulaimans and the Kirthars is becoming unimportant but that of the Himalayas continues strong.

The westerly winds have everywhere increased in strength, without any appreciable change in the position of maximum velocities (12 m/s at this level). The anticyclonic belt has moved southward and the easterly winds in the south of the Bay have weakened.

4, 6 and 8 km.—With increasing height, the westerly circulation becomes stronger and more and more zonal and the anticyclonic belt is gradually pushed southward. Even at 4 km, the control exercised by the Hindukush and the Himalayas is large, as will be seen by the weakness of winds at Lahore, Peshawar and Simla compared with those at Quetta and Agra. The normal wind velocity at 4 km at Quetta is 7 m/s, while at Peshawar it is only 4 m/s. At 8 km, which is well above the average height of the Himalayas, while there is little difference of wind velocity between Quetta, Lahore, Simla and Peshawar, the zone of maximum wind strength remains at 25-27°N. This does not appear to be a mere effect of the Himalayas in obstructing the air movement but is a feature of the upper air circulation in winter caused by the distribution of temperature.

Cloud Winds.

Comparing cloud winds with pilot balloon winds at corresponding levels, the most important feature is the greater frequency of occurrence of southerly components of wind during cloudy weather. This is particularly evident at the low-cloud level in the Punjab and at all levels in the Deccan, north-east India and Burma. In a general way, it may be said that in cloudy weather, the anticyclone is on the mean displaced eastwards and the easterly air in the south of the Bay tends to move north and northeastwards and join the westerly stream of upper India.

Some local peculiarities of wind structure.

(*a*) Winds in the Punjab.—The plains of the Punjab, being enclosed on their west, north and east by high mountains and open towards the south, form a sheltered area for wind at levels below the surrounding mountains. A little farther south, the westerly winds are less restricted in their movement, and there is consequently a tendency for a cyclonic vortex to be formed in the Punjab especially when there is an acceleration of wind as in front of an advancing depression. Southerly winds are more frequent in the east Punjab than in the west and precipitation is also heavier on the hills on the eastern side. It is instructive to compare the frequencies of winds from different directions at Agra, Lahore and Simla, (*Table 1*).

TABLE 1.

Percentage frequencies of winds from different directions, in January.

	N	NE	E	SE	S	SW	W	NW
			Agra.					
1 km	12	3	8	9	8	3	12	43
2 „	4	1	3	2	10	13	31	36
3 „	4	1	..	..	2	17	48	27
4 „	..	..	..	..	..	16	60	19
6 „	1	..	..	..	..	11	75	14

Percentage frequencies of winds from different directions, in January—contd.

	N	NE	E	SE	S	SW	W	NW
			Lahore.					
1 km	13	7	5	8	4	3	14	40
2 „	10	6	6	10	12	13	14	23
3 „	9	1	1	4	17	18	28	19
4 „	..	..	..	..	7	19	35	22
6 „	..	..	..	..	1	15	58	22
			Simla.					
3 km	5	3	6	34	17	6	6	16
4 „	1	..	2	13	11	8	10	17
6 „	1	..	..	..	3	18	56	18

The greater frequency of winds from southerly directions at Simla and Lahore may be noted.

(*b*) Katabatic winds in the Brahmaputra valley.—Mention has already been made of the katabatic winds in the Brahmaputra valley. The direction of this valley, which runs approximately against the direction of the prevailing upper winds, favours the maintenance of these winds. A stable stream of fluid flowing towards the closed end of a channel will partly flow over the end wall, but the accumulation of fluid on the upstream side of the wall will also set up a return eddy current. When the sides and tops of the surrounding hill are d fferentially cooled (by the effect of radiation) the flow of cooled air down the hill slopes will facilitate the return flow. The easterly current is generally more than 2 km thick at Tezpur, which lies near the middle of the valley, and about 1 km thick at Rangpur near the mouth of the valley. Naturally, both the thickness and strength of the current will be variable, depending on the strength of the upper current and the stability of the air. At the interface between the westerly upper current and the easterly lower current, waves will easily form just as in the ' Totwasser ' of Norwegian fjords.[15] Aeroplanes would therefore experience bumpiness near the places and levels where the easterly and westerly streams meet. The following table (*Table 2*) gives the frequencies of winds from different directions at 0·5, 1, 2 and 3 km in January 1930, at Tezpur, Rangpur and Patna.

TABLE 2.

Frequencies of wind from different directions at Tezpur, Rangpur and Patna in January, 1930.

—	n	N	NE	E	SE	S	SW	W	NW	<1·4m/s
				0·5 km.						
Tezpur	28	..	2	20	1	1	1	2	..	1
Rangpur	30	3	4	7	1	2	2	4	1	6
Patna	31	..	..	1	2	1	1	13	7	6
				1 km.						
Tezpur	28	..	1	17	1	2	2	1	..	4
Rangpur . . .	30	2	2	8	4	1	3	4	1	5
Patna	31	1	..	1	1	..	2	19	5	2
				2 km.						
Tezpur	27	..	1	14	1	1	2	1	..	7
Rangpur	29	2	2	5	..	1	..	11	8	..
Patna	31	..	..	..	..	..	1	13	17	..
				3 km.						
Tezpur	24	1	2	6	1	1	2	9	..	2
Rangpur	26	..	1	..	..	..	..	19	6	..
Patna	30	..	..	..	..	..	..	18	12	..

These valley winds are most marked in the winter months November to February. Similar but shallower return currents also form in the Silchar valley.

Temperature Distribution.

At all levels up to 6 km, the temperature generally decreases towards the north. At 1 km, there is an area of maximum temperature lying over the Deccan and an area of weak horizontal gradient in north-west India. As the height increases, both these features become less and less prominent and ultimately disappear leaving a simple system of temperature distribution, the temperatures decreasing towards the north with gradually increasing horizontal gradients.

Thick incursions of moist air in the south of the Bay from across Tenasserim, which occur very occasionally, lead to the formation of a warm front between this air and the north-easterly streams blowing towards the Madras coast from the head of the Bay.[16]

FEBRUARY.

Conditions in February are generally similar to those in January and we shall not give a detailed description of them.

C

MARCH.

March is also a month of settled weather over the Indian seas. Western disturbances continue to pass eastwards across north India. The surface pressure gradient is weak over most of the area.

Upper Winds.

The main difference of upper air conditions in March from those of January is the setting up of an inflow of wind from sea to land in the coastal districts in the first one kilometre. This is better shown in the afternoon wind charts which are however not reproduced here. The highest temperatures at the surface and at 1 and 2 km occur in the middle of the Deccan in latitudes of 15-17°N. The stream-line chart at 1 km shows air in Gujarat and Bombay Deccan flowing southward, while along the east coast of the Peninsula it moves northward. Occasionally, this causes even the winds in South Bengal and Assam to flow northeastwards towards the hills. This is more marked in the succeeding months April and May.

In Burma also, ground heating is responsible for the development of a shallow low. The winds at Akyab at 1 km remain northerly to northwesterly, while those at Rangoon and Mandalay show that the mean air movement in the Irrawady valley has become southerly.

On the Mekran and Sind coasts there is a slight increase of wind strength at 1 km compared to the previous two months.

In spite of the marked difference in the stream lines at 1 km between January and March, the difference is small at 2 km and above. The only noteworthy changes are the decrease of wind strength in the region of westerly winds and an increase of strength of the northeasterly to easterly winds in the south of the Peninsula at 3 and 4 km.

Temperature Distribution.

As regards temperature distribution, there is a closed region of high temperature in the Peninsula at 1 and 2 km. At higher levels, the temperature regularly decreases towards the north. Temperature gradients are weaker than in January. At 6 km over the same latitude, the isotherms indicate slightly higher temperatures when the air has been over sea than over land.

APRIL.

In April, storms originate occasionally in the Bay of Bengal between latitudes 10° and 15°N, especially in the latter half of the month, and generally move northwards and northeastwards towards the Arakan coast. The closed area of high temperature in the middle of the country is more intense and deeper than in March and is displaced slightly northward. There are corresponding alterations of air movement in the first two kilometres, the southerly component of wind at 1 km being stronger all along the east coast, in Bengal and in Burma and the northeasterly winds at 2 km in the south of the Peninsula being weaker. As these features become more pronounced in May, we shall pass on to consider the conditions in that month.

MAY.

Storms in Indian seas are common in this month. In the Bay of Bengal, they originate between latitudes 10° and 15°N. They generally have a northwesterly course in the beginning of their career, which later changes to northerly and still later to northeasterly.

The majority of them strike land on the Arakan coast, but many strike the Madras and Orissa coasts also. Once they reach the Indian coast, they show little tendency to penetrate inland but move parallel to the coast northeastwards as weak depressions. In the Arabian Sea, they generally move northwestward towards the Arabian coast. The monsoon usually breaks on the Malabar coast in the last week of May and in Tenasserim in lower Burma a few days earlier. The advances of the monsoon along the west coasts of India and Burma are often accompanied by storms.

Upper Winds.

1 km.—In May, the area of highest temperature at the surface, and at 1 and 2 km lies in an elongated form, running from Central India to Baluchistan and Persia. With the northward shift of the area of maximum temperature the system of coastal winds at 1 km in the Peninsula gets transformed into one of northwesterly to southwesterly winds traversing the whole breadth of the Peninsula, and the winds in the Persian Gulf, the Mekran and Sind coasts and the whole of the Peninsula become steadier and stronger. This is the first stage in the transformation of local land and sea-breezes into the south-west monsoon system of circulation.

In Bengal and Assam also, the afternoon southerly to southwesterly breezes which begin even in March, gain in steadiness and strength in April and May, the mean velocities of morning winds at 1 km in May being about 6 m/s.

2, 3 and 4 km.—2, 3 and 4 km may advantageously be considered together. At all these levels, the main points of difference from April are (i) the more frequent incursion of southerly and southwesterly winds in the south of the Bay of Bengal, (ii) the increased flow of air into the Peninsula and the west Bay of Bengal from north India and (iii) the marked weakening of the westerly to northwesterly winds at these levels in Bengal and Assam. *Table 3* gives the mean percentage frequencies of winds at 2 km in April and May at Waltair, Madras and Port Blair, which show clearly that while in April the frequencies of winds from different directions at Port Blair and Madras are similar, in May there is a greater frequency of southerly winds at Port Blair and of northerly winds at Madras.

TABLE 3.

Percentage frequencies of winds from different directions at 2 km.

—	N	NE	E	SE	S	SW	W	NW
			April.					
Waltair	14	4	4	4	11	..	11	23
Madras	6	28	37	19	2	2	5	1
Port Blair . . .	7	22	36	14	3	8	5	5
			May.					
Waltair	6	6	..	12	..	12	29	36
Madras	18	23	13	8	2	2	8	21
Port Blair . . .	10	5	12	15	6	13	17	12

At all these levels and also at 6 km, the sweep of the northwesterly continental winds normally extends over an area bounded on the South by a line running from the north of Ceylon to Pegu in Burma. Storms in this month usually form a little to the south of this line.

6 and 8 km.—The westerly winds at these levels throughout north India have diminished in strength, the decrease being most marked over Bengal and Assam. For example, the mean wind velocity at 6 km over this region is 12 m/s in April and 8 to 4 m/s in May, the velocity decreasing towards the east.

Temperature Distribution.

Upper air temperatures in this month (May) show some very interesting features. As mentioned already, at the ground, 1 and 2 km, the area of maximum temperature lies over Central India, Sind and Baluchistan. The temperature falls most rapidly towards Bengal and Assam and also towards the south-east Bay of Bengal. At 3 km, while the area of highest and lowest temperatures remain over Baluchistan and Assam respectively, the gradients have become much weaker. At 4 km, the distribution of temperature is somewhat similar to that at 3 km, but the area of lowest temperature has moved westwards from Assam towards the United Provinces and the rate of fall of temperature from the south Bay towards the north has increased. At 6 km, the *highest* temperatures are over Assam and upper Burma and the lowest over the Punjab and Kashmir—almost a complete reversal of the distribution in the first 2 kilometres.

The high temperature of the atmosphere at 6 km (and presumably also at higher levels) over south Bengal, Assam and upper Burma is no doubt to be attributed to the heat energy released in the upper atmosphere by the frequent thunderstorms which occur in April and May in north-east India and upper Burma. As the prevailing winds at these levels are westerly to northwesterly, it may be expected that the area of highest temperature would be displaced slightly down-stream.

In the light of the upper air information clearly brought out by the charts, a few remarks may be made regarding two conspicuous weather phenomena of this month, namely, the occurrence of Nor'wester thunderstorms in Bengal and the origin of pre-monsoon storms in the Bay of Bengal.

In trying to explain the Nor'westers of Bengal, Blanford wrote : " In March and April too, they (northwesterly winds) frequently blow, as dry winds, right across north India to Bengal, but are rarely felt in the Gangetic delta itself since they pursue their eastward course at the higher level attained on the Chota Nagpur plateau, while the sea-winds from the coast creep in beneath and eddying with the westerly winds, give rise to the local storms called Nor'westers, which are so characteristic of the spring months in lower Bengal ".[17] Mere eddying cannot give rise to the enormous energies released in these thunderstorms and we have to seek further causes for the occurrence of these phenomena. The stream-line charts and wind-roses in May show that air in the first kilometre, though of continental origin, has passed over distances up to about 1,500 km over the Bay of Bengal (and perhaps also a similar distance over the Arabian Sea before entering the north of the Peninsula) ; but the air at 2 to 4 km most frequently comes straight from north-west India. The effect of the passage of the surface layer of air over the sea is to convert part of its heat energy into energy of moisture-content. This addition of moisture in the

lowest layer is very important from the point of view of possible thunderstorm formation. An inversion would however form between this surface layer and the drier northwesterly air above. During day owing to solar heating further energy is added to the surface air in the form of temperature increase ; there is an increase of lapse-rate in the surface layers and the inversion is reduced in intensity or even gets wiped out enabling a penetration of moisture above the original level of the inversion.

Above 4 km, we note that northwesterly winds are less common, the direction of maximum frequency of upper wind at Calcutta being westerly at 6 km and southwesterly at 10 km. We also note from the charts of isotherms that at 6 km, the air over Bengal is markedly warmer than that over north-west India. There is little doubt that this is true at 8 and 10 km also. The increased temperature in the higher layers would only have the effect of increasing the comparative stability of the atmosphere over Bengal. How then does it come about that in this month thunderstorms in Bengal are more common and violent than those elsewhere ? The concentration of energy exists essentially in the accumulation of water vapour in the lower atmosphere, the persistence of the southerly stream in the first kilometre keeping up the supply of moisture. But before the energy can be made available, the stability of the upper atmosphere must first be reduced by replacing the air at the upper levels by cooler air (the wind-roses suggest that this generally happens at 6 km and above) and by breaking down the inversion between the southerly moist surface air and the superincumbent drier air. To some extent, the breaking down of the inversion takes place every afternoon by the effect of insolation and the thickening of the southerly stream owing to sea-breeze. The fact that the thunderstorms do not happen every day shows that the replacement of the warmer air above 6 km by colder air occurs only in spells. When a deeper surface stream enters Bengal, as for example owing to the effect of a depression and this happens to coincide with a fall of temperature above 6 km, the release of energy will naturally be greater.*

Pre-Monsoon Storms.

For the formation of storms in the Bay of Bengal in this month, the importance of the flow of north-west Indian dry air at 2 to 6 km into the Bay of Bengal has been pointed out in a paper on pre-monsoon storms by one of the authors and Banerjee.[18] The isotherms at different levels show that rapid flow of air at 6 km. from northwest India into the Bay will lead to extensive cooling at the top and hence to instability. The storms are often associated with an inflow of moist air from some southerly direction of more than 3 km thickness. But whether this inflow is a *necessary* preliminary for the formation of storms has not yet been ascertained.

JUNE.

Before the middle of June, the southwest monsoon normally advances to Bombay on the west coast and penetrates into Burma, Assam and Bengal. By the end of the month it generally affects the whole country except the region west of Rajputana and the Punjab.

* A lucid discussion of " latent instability " and the energy realisable from it is contained in Dr. C. W. B. Normand's presidential address on " The Sources of energy of storms " before the Mathematics and Physics Section of the Indian Science Congress, January 1938 (Proc. Ind. Sci. Congr., 1938). Mr. G. Chatterjee and Dr. N. K. Sur have also recently discussed (Mem. Ind. Met. Dep. Vol. 26, Part 9) the upper air conditions over Bengal in the Nor'wester months with particular reference to latent instability.

Storms in the Bay of Bengal in this month usually originate or strengthen in the extreme north of the Bay where the northwesterly winds from land reach the southwesterly winds at 2 and 3 km.

Temperature Distribution.

As in May, the region of highest temperature at 1 km lies over north-west India and the temperatures fall towards south and east. The gradients are larger than in May. The lowest temperatures lie over the south-east Bay of Bengal and probably also over the south Arabian Sea. With increasing height, the gradient decreases, and at 4 km there is practically no difference of temperature between different parts of the country. At 6 km, the gradients are reversed, the highest temperatures being over Assam and the lowest over the N. W. Frontier Province. In the north Arabian Sea also there is a temperature fall towards Baluchistan and Persia. The winds at 2 and 3 km coming into the north-west corner of the Bay of Bengal from Rajputana and the United Provinces will therefore be bringing air warmer than the southwesterly air, while at 6 km and above the air coming from the south and east will be warmer than the air from the northwest.

JULY.

Upper air conditions in this month have been fairly exhaustively discussed in a previous paper by the authors.[4] We would, however, like to direct attention to a few points.

(i) The heat low over north-west India is shallow, the cyclonic circulation at 1 km being replaced by an anticyclonic circulation at 2 km and above. The low pressure trough parallel to the Gangetic valley is deeper and is progressively displaced towards the south as the height increases from 1 to 4 km ; it practically disappears at 6 km.

(ii) At 3 km and above, the boundary between the old monsoon air and the northerly air from Persia and Afghanistan lies in a northeasterly direction a little to the south of Karachi. The winds at Karachi at 3 km and above are abnormally strong and this feature is perhaps due to the convergence of air from two different sources.

(iii) Cloud winds show only small differences from pilot balloon winds at corresponding levels. Comparing low cloud directions with winds at 1 km, it is seen that the former show a greater frequency of easterly than westerly winds in the United Provinces and the Punjab. The middle cloud movement corresponds to the mean of the pilot balloon movements at 4 and 6 km. High clouds move similarly to pilot balloon winds at 8 km, but the easterly winds in north India push farther westward, the cirrus winds in the Persian Gulf showing a greater frequency of easterlies.

Temperature Distribution.

At 1 km, the main feature of the distribution is the regular fall of temperature eastward from Baluchistan to Assam and Burma and southward along the west ast of the Peninsula towards Malabar. At 2 km, the isotherms have changed their ection running now from WSW to ENE. At 3 km the excess of temperature in rth-west India over that in the north-east has vanished and latitude for latitude,

temperatures in the eastern part of the Bay of Bengal are higher than those over the east Arabian Sea. At higher levels, the relative warmth over north-east India increases, with the result that at 6 km the highest temperatures are found over Bengal and the United Provinces. By the time that the monsoon air arriving in the lower levels in the south Arabian Sea and south-west Bay of Bengal as the south-west monsoon has moved up to this region, it has shed a considerable fraction of its moisture and converted its energy of moisture-content in the lower levels to energy of temperature in the higher.

AUGUST.

The monsoon has its farthest northward extension in August. Both in July and August, depressions either originate in the Bay of Bengal off the Orissa-Bengal coast or develop there out of low pressure areas which cross over from the China Sea across Burma[19]. They generally move in a west-northwesterly direction to the eastern side of the Aravallis and, after a day or two of persistence there, move either towards the Punjab or cross over to Sind. The very small area within which different depressions originate or strengthen and the narrowness of the belt along which they travel are noteworthy.

The wind and temperature distributions of August do not show any essential differences from those in July.

SEPTEMBER.

The southward movement of the monsoon begins about the end of August; by the end of September the monsoon is confined to the east and southeast of a line running approximately from Bombay to Shillong. The retreat is effected by the pushing back of the moist currents by drier air from the north-west. Depressions or storms are fairly common in the Bay of Bengal; the region where they originate or strengthen is more widely spread out than in July or August.

Upper Winds.

1 km.—With the southward retreat of the sun, and the increased nocturnal radiation from the Asiatic plateaux the region of highest temperature in the first kilometre is displaced eastwards from Baluchistan and Sind and now lies partly over Rajputana. The Punjab, Sind and Rajputana are over-run by weak northwesterly winds. The shallow cyclonic circulation which lay over Sind in the previous three months, exists now at 1 km in a feeble form over the east United Provinces and Bihar. In the rest of the country, the mean winds are nearly the same as in July but are weaker everywhere and inclined to be more northwesterly in the Peninsula.

2 km.—The circulation at 2 km shows cyclonic movement over the northwest of the Bay. Northwesterly or northerly air cover the whole land area west of the United Provinces and Central India. Occasionally, the northwesterly air reaches out to the Bay.

3 and 4 km.—At 3 and 4 km, the northwesterly land air penetrates farther south into the Peninsula. The southwest monsoon current has weakened considerably and there are only feeble southerly currents in the eastern half of the Bay, Burma and north-east India. In keeping with the diffuseness of the semi-permanent cyclonic circulation at all these levels, caused no doubt by its position away from the mountains to the north and north-east, diffuse depressions often develop over the Bay of Bengal, move slowly westwards across the Peninsula and emerge into the Arabian Sea giving rise to widespread rainfall associated with thunder. The rainfall is generally confined to the east of the region of winds

of north-westerly origin and the separation between the region of rain and no rain is often very sharp.

6 and 8 km.—The southerly stream over the east Bay of Bengal and Burma has vanished at 6 km and been replaced by a general easterly current similar to what we had in July and August but now confined to latitudes south of 23°N. Over the Punjab, the westerly circulation of temperate latitudes has already invaded and a saddle-shaped system of stream-lines is formed over north India with northwesterly air moving southwards over Iraq, Persia and Baluchistan to join the easterlies over the Arabian Sea and with the easterly tropical stream in lower Burma and the Bay turning northward and changing to westerly over north-east India and upper Burma. The stream-lines at 8 km are similar, but there is a marked strengthening of the westerly winds over the Punjab. The tropical easterlies also show increase in strength, though less conspicuously than the westerlies in the north.

Temperature Distribution.

The upper air temperature distribution in September is qualitatively similar to that in July or August but shows some changes as regards the positions of the highest and lowest temperatures and the magnitudes of the gradients. At 1 km, the warmest air lies over northwest India, but displaced eastwards ; and the coldest is over lower Burma and the south-east Bay of Bengal. At 2 km. the direction of the gradients changes to more nearly north and south. A separate centre of high temperature makes its appearance over north-east India at 3 km. There is no horizontal gradient to speak of at 4 km, but strong gradients have developed in northwest India at 6 km with temperatures falling towards the northwest Frontier.

OCTOBER.

In this month, air currents of land origin cover northwest and central India and a good part of the Deccan and the monsoon has definitely withdrawn from most parts of north India and from the central parts of the country. October and November are the months when severe storms are most frequent both in the Bay of Bengal and in the Arabian Sea. In October, the storms generally originate south of latitude 16°N. They are often continuations of storms in the China Seas which enter the Bay of Bengal across Tenasserim.

The most striking feature of the stream-lines of this month is the greater strength of the north and south components compared to those of the east and west at 1, 2 and 3 km.

1 km.—At 1 km, air flows from north to south in regions lying approximately to the west of longitude 85° and from south to north to its east. A feeble cyclonic circulation exists in the Bay of Bengal off the Carnatic coast, the weakness of the resultant winds in this region being chiefly due to the variability of wind.

2 and 3 km.—At higher levels, the westerly winds in north India push through to Bengal and Assam and a system of saddle-shaped stream-lines develops with its neutral point over the Bay of Bengal. The development of depressions in the Bay is usually accompanied by an influx of southerly to southeasterly winds in the Andaman Sea. The following table (*Table 4*) giving the percentage frequencies of wind over Madras and Port Blair at 1, 2 and 3 km is instructive as showing the variability of wind direction at the two places.

TABLE 4.

Percentage frequencies of winds from different directions at Port Blair and Madras.

——	n.	N.	NE.	E.	SE.	S.	SW.	W.	NW.
				Port Blair.					
1 km . .	109	3	6	18	10	8	21	19	8
2 km . .	96	4	5	18	12	13	15	18	4
3 km . .	84	6	13	21	12	6	16	13	5
				Madras.					
1 km . .	103	14	31	10	2	5	8	11	18
2 km . .	101	29	20	12	3	0	7	11	14
3 km . .	90	14	12	14	4	2	4	20	22

4, 6 and 8 km.—At still higher levels, the westerly winds in north India rapidly gain in strength and also encroach towards lower latitudes. In the south of the Bay, the winds become systematically easterly. As a result, the zonal movement becomes more important than the meridional.

Temperature Distribution.

The horizontal gradients of temperature are generally very weak in this month, especially in the first three kilometres. At 1 km, there is a weak gradient of falling temperature from Central India and the west United Provinces towards the Bay of Bengal. Even this gradient vanishes at 2 km. At 3 km, a temperature rise towards the south is noticed in the extreme north of the country ; this extends southwards at 4 km towards the Bay of Bengal. The same kind of distribution exists also at 6 km, but the gradients are stronger in north India.

NOVEMBER.

November is the month in which the north-east monsoon is most active in the south Bay of Bengal and the east Madras Coast. It is also a month of severe storms in the Bay of Bengal, their places of origin or strength being generally south of latitude 13°N.

Upper Winds.

1 and 2 km.—Compared with October, there is an increase of mean wind velocity in all parts of the country except on the Mekran and the Persian Gulf coasts. Valley winds are conspicuous in Assam between the Khasi hills and the Himalayas both at 1 and 2 km. The land air from north-west India curves round the high pressure area in the central parts of the country and traverses the middle of the Peninsula as a northeasterly current. The

wind directions in the south Bay and on the Madras coast have become definitely easterly and north-easterly and the wind speeds are also higher. When the north-east monsoon is active, these easterlies are generally a continuation of the NE trades of the Pacific as is shown by the upper air wind roses at Manila and Guam[20] and the rainfall distribution in Siam and Cochin-China. At intervals between spells of activity, the Chinese anticyclone tends to spread towards the south in Cochin-China and Siam. When storms in the Bay approach the Madras coast south-westerly winds are sometimes stimulated in the extreme south of the Peninsula and in Ceylon.

3 to 8 km.—With increasing height, the north-westerly and westerly winds of north India gradually strengthen and extend southwards and the deformation field of velocity becomes more and more pulled out along the latitudes. A comparison of the circulations in north-east India and Burma in October and November shows that the supply of easterly trade air from the south of the Bay is more easily deflected northwards in the former month than in the latter.

When storms from the Gulf of Siam enter the Bay of Bengal in November and recurve towards the north and north-east, we observe that their movement corresponds more nearly to the mean upper air movement in October than in November.

Temperature Distribution.

In this month, north India has definitely become cooler than the south at all the levels considered. At 1 km, rising gradients in the Bay are from north-west to south-east, but at higher levels, they are everywhere from north to south. At 3 km and above, the gradients south of 20°N are very weak. There is just a suggestion of maximum temperature in the middle of the Bay at 4 km.

DECEMBER.

From November to December the main change that occurs is the southward movement of the region of westerly winds which is very evident in the charts at 3 to 8 km. There is simultaneously a southward retreat of the easterly moist sea winds in the south of the Bay in the lower levels although it is not clear from the wind charts alone that part of the easterlies at 1, 2 and 3 km in December is derived from the anticyclonic air of Cochin-China and Siam.

Discussion of the main features of the circulation.

It would be useful to summarise the important features of the circulation which are brought out by this survey. The area studied extends roughly from latitude 8°N to 35°N and longitude 50°E to 100°E and includes part of the tropics, the sub-tropics and part of the temperate regions.

(i) The most striking feature of the circulation is the regular seasonal northward and southward movement of the upper wind system. The movement cannot correctly be described as meridional ; in the summer half of the year, the singularities of the system move from south-east to north-west and back, while in the other half, the movement is mainly meridional. The following table gives the latitudes at which the west-east component of wind vanishes at different heights above sea-level over the longitude of Agra, *viz.*, 78°E.

TABLE 5.

The maximum northerly latitude to which easterly winds extend (Long. 78°E).

Height (km.)	Latitude (degrees north).											
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
0 . .	25	25	25	×	×	×	×	×	×	24	24	24
1 . .	21	21	20 (?)	×	×	×	×	×	×	25	25	24
2 . .	18	17	18	18	×	×	×	×	26	23	23	20
3 . .	16	16	17	18	18	22	30	30	26	23	21	18
4 . .	15	15	16	18	18	22	29	30	26	20	19	16
6 . .	12	12	13	14	17	21	29	29	25	19	17	15
8 . .	11	11	11	11	15	21	28	29	24	18	16	12

The smallness of the meridional shift, from month to month, of the transition zones in the upper air during the dry period from December to April (and even in May) is remarkable and shows that the radiational cooling of the ground in winter and the insolational heating in the hot season do not make any profound modification in the circulation. The big changes come in only with the advent and northward penetration of moist air and attendant rainfall in June and July.

Ground heating by itself rarely affects upper air conditions to a height greater than 4 km, ground cooling affects them to a much smaller height. When ground heating is combined with supply of moist air in the lower layers important modifications take place.

(ii) A very striking feature of the circulation in this region throughout the year is the great influence exercised by the mountain system on the north up to a level of 6 km. This is seen alike in the mean movement of air parallel to the Himalayas during the winter and hot season, and in the existence during this period of a region of maximum wind strength up to 6 km in the east United Provinces and Bihar and also in the localisation of the monsoon low to within the confines of India.

(iii) Regions of heavy rainfall become regions of high temperature and also of divergence of air in levels above 6 km. Stream line and temperature charts in May to September provide examples of this.

(iv) During winter and hot season, the pilot balloon winds show that, on the mean, the winds of the westerly circulation of the higher latitudes turn towards the south and southwest and join the easterly circulation. In cloudy weather in this period the opposite is the case, air coming from the east turning towards the north and northeast. Cloud winds generally show a longer meridional stretch than pilot balloon winds.

West of longitude 70°E, the mean air movement over the land areas as shown by pilot balloon winds is in all the months northerly, carrying air from higher to lower latitudes. Even cloud winds do not show any large movement from the south except during the post-

monsoon period and, considering the small frequency of clouds in this region, it appears that on the aggregate the net transport of air is from north to south in this region up to a height of 8 km.

In a similar way, there is little doubt that east of longitude 90°E, the net effect of the circulation is to transport air from south to north during the period January to October.

Pilot balloon winds at higher levels over Poona show that, even in the dry season, there is on the aggregate a poleward flow of air above 8 km.*

We shall now make a brief comparison of upper air conditions in this region with conditions in corresponding latitudes in some other parts of the northern hemisphere.

The semi-permanent sub-tropical anticyclones of the northern hemisphere are located at ground-level during winter at latitudes varying from 25°N to 35°N over the oceans and extend over neighbouring land areas (we are excluding from our consideration the great continental anticyclones which lie north of latitude 40°N over Asia and North America). According to the charts of cirrus movement prepared by van Bemmelen, these anticyclones exist in the cirrus level (and during cirrus weather) in winter over latitudes varying from 15° to 20°N. Over India and neighbouring regions the position of the winter anticyclone is about 25°N at the ground, 16—18°N at 2 to 3 km and 11—12° N at 8 km. They are thus located at lower latitudes over India and its neighbourhood.

In *Figs. 3* to *8* are shown the distribution of westerly and easterly components of winds at different levels and at latitudes varying from 10° to 30°N over the meridian 78°E. The charts are drawn for six months of the year. The values of the W-E wind components in metres per second are given by the figures in the appropriate places, positive values signifying easterly winds and negative values westerlies. In the winter and hot seasons, the westerly winds penetrate farther southward at higher levels, and the greater the velocities of the westerlies at say 25°N, the farther is the southward limit of penetration. This is similar to what has been found elsewhere, for example, over the Atlantic [21], but the strengths of the westerly winds over north India are markedly greater than those found in similar latitudes over the Atlantic Ocean.

As the lower wind system up to 4 km in the months November-April has many points of similarity with the trades, it is desirable to examine whether there are any winds corresponding to the anti-trades of the Atlantic. As mentioned already, over the region of longitudes 45°—80°E the upper westerlies come more often from the north than from the south, while east of longitude 90°E, southwesterlies are more common. It also appears that it is only in cloudy weather that the easterlies and westerlies over the Indian Peninsula have very different origins. In clear weather, the air coming from the east is also often westerly air which has turned round, first southward and then westward. Unless we choose to call all the upper westerly winds anti-trades, we do not have a regular anti-trade wind system moving from lower to higher latitudes up to 8 km, except in times of cloudy weather. The general process of circulation between the westerlies and easterlies can be described as follows. At the lower levels, the westerly air moves southwards more directly than at higher levels. As it moves south, it rises owing to gain of heat and then turns round the anticyclone towards the north and joins the westerlies. It again moves slowly towards

* It is desirable that the question be more quantitatively examined taking into consideration the relative frequencies of pilot balloon and cloudy days.

the south, gains heat, and again turns round the anticyclone at a higher level and a lower latitude. This goes on until it either reaches a region of longitudes where the anti-trades are well-developed or gets caught in the northward moving air associated with a disturbance. The probable life-history of the air is shown in *Fig. 2.*

Bjerknes and collaborators[22] have calculated the distribution of pressure in the free atmosphere in a meridional section on the basis of the surface pressure distribution and the distribution of temperature in the atmosphere up to 25 km ; and by application of the gradient wind formula have also calculated the wind field. The good general agreement of the observed wind-system with the calculated wind-system shows that, for a correct understanding of the general permanent circulation of the atmosphere, the ascertainment of the exact distributions of temperature in different regions of the earth and the assignment of the correct physical causes for them are of fundamental importance. In this connection, attention may once again be drawn to the important result brought out from the sounding balloon results in India, namely, that the highest temperatures in the tropical troposphere at levels between 6 and 13 km are found over regions of extensive rainfall. The highest pressures at the levels are also found over the same or near regions. The physical reason for this is that lapse-rates over regions of heavy rainfall tend to come down to those appropriate to saturation adiabatic. We have therefore to seek for regions of highest pressure in the upper atmosphere *at these levels* in other parts of the tropics in similar regions of heavy widespread rainfall, such as parts of Africa, East and West Indies, Brazil, etc. With the seasonal movement of rainfall, areas, the high pressure areas at these levels will also move correspondingly. This is borne out by our 8 km charts and also by van Bemmelen's charts of cirrus movement.

Acknowledgment.

The present work is based on a large amount of observational material, collected over a period of 20 years and from an area extending from the Persian Gulf to lower Burma and from the North-West Frontier Province to Travancore. As such, it rests on the work of a large number of individuals and the authors are deeply conscious of their indebtedness to others. The late Mr. Field, the pioneer of upper air investigation in India, and Mr. G. Chatterjee, his successor as head of the Agra Observatory and organiser of upper air work in India, together with the staff of the various Upper Air Observatories, have built up this great bulk of observational material. In the preparation of the paper itself, most of the members of the Upper Air Section, Poona, have assisted in various ways ; the constant and whole-hearted assistance rendered by the late Mr. L. V. Joshi has been particularly valuable. The authors are grateful to Dr. C. W. B. Normand, Director-General of Observatories, for the encouraging interest taken by him in the work ; and to Dr. N. K. Sur for generously placing at their disposal some of the tables in *Appendix B* which were prepared in the Upper Air Section during the period of his charge.

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APPENDIX A.

Explanation of the symbols used in Appendix A.

n gives the number or observations,

V the arithmetic mean speed irrespective of direction in metres per second,

v the resultant velocity taking account of direction in metres per second,

D the resultant direction in degrees east of north, and

D′, D″ two most representative directions.

When two adjacent directions, say N and NW, are both more frequent than an altogether different direction, say S, and the last is also fairly frequent, NNW and S have been given as D′ and D″ instead of N and N W. When two directions are almost equally frequent, the direction from which stronger winds blow has been given first. A few cases have been indicated like NW—E. This means that winds blow mostly from the directions included between the first and the second as we go clockwise.

Var. means variable.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	62	6·5	6·3	88	E		40	6·2	5·5	81	E	NE	21	5·0	1·5	30	ENE	Var.
Bahrein	211	8·1	3·0	324	NNW	SSE	206	7·7	3·1	286	NNW	SSW	174	8·7	6·4	272	SW—NW	
Muscat	203	4·0	1·3	290	WNW	Var.	200	4·5	1·5	301	WNW	Var.	174	6·4	4·2	285	SW—NW	
Gwador	213	5·0	1·2	344	Var.		205	5·9	1·9	313	Var.		177	8·2	6·7	289	WNW	
Karachi*	279	6·8	3·4	24	W—N—E		277	5·7	2·4	335	W—N—E		268	6·6	4·3	286	SW—N	
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	272	3·7	1·4	255	NW/N	S
Peshawar*	269	2·2	0·2	166	..	..	271	3·0	2·2	321	W—N		264	4·1	2·3	344	NW—E	
Lahore*	388	4·7	2·5	333	NW	N	393	4·4	1·9	314	NW	Var.	375	4·6	1·4	255	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	61	6·7	4·2	317	NW	Var.	60	6·6	4·5	298	NW	Var.	58	6·7	5·1	280	S—NW	
Ahmedabad	185	6·2	3·2	52	NW—E		185	4·6	0·9	305	Var.		183	7·1	4·6	256	S—NW	
Ajmer	..	..	..	..	..	..	186	5·0	0·8	271	Var.		185	7·5	5·6	268	SW—NW	
Agra*	510	5·7	2·5	346	NNW	SE	509	5·5	2·4	309	NW	Var.	502	7·2	5·3	278	S—NW	
Allahabad	121	5·5	2·2	314	NW/W	ESE	122	6·0	4·5	297	WNW	Var.	116	10·5	9·4	290	NW	W
Patna	183	5·2	2·7	293	WNW	ESE	182	6·2	5·0	290	W	NW	180	11·6	11·1	293	NW	W
Rangpur	36	3·6	0·9	39	Var.		36	3·3	0·1	297	ESE	W	34	6·4	4·7	292	WNW	E
Tezpur	142	3·9	2·6	90	E		142	3·8	1·5	91	E/NE	Var.	131	4·6	0·4	145	E/NE	SW
Calcutta*	327	4·9	2·7	344	N	Var.	326	5·2	3·8	318	NNW	Var.	302	8·8	7·8	302	NW	W
Dacca	180	3·8	2·3	327	N	Var.	178	4·4	3·4	303	SW—N		172	10·1	9·3	294	NW	W
Chittagong	186	4·2	3·1	1	N	Var.	185	4·6	3·4	327	NNW	Var.	171	8·1	7·0	296	WNW	Var.
Akyab*	335	4·6	3·2	3	N	Var.	335	4·7	2·4	328	NNW	Var.	331	6·7	4·4	297	SW—N	
Mandalay	184	3·3	2·1	166	S/SE	N/NE	186	3·6	1·7	201	S/SW	N/NW	185	6·2	5·2	234	S—W	
Rangoon	175	4·3	1·4	31	NNE	Var.	175	3·9	1·9	107	SSE	Var.	174	4·7	1·8	200	S	Var.
Jubbulpore	..	..	..	..	..	..	186	5·0	0·7	260	NNE	SSW	184	7·9	5·9	274	SW—NW	
Ranchi	..	..	..	..	..	..	34	7·3	5·7	297	NW	W	33	12·1	11·1	287	NW	W
Sambalpur	120	3·5	0·7	350	N	Var.	120	4·2	2·3	309	NNW	Var.	120	6·9	5·2	320	NW	Var.
Poona*	..	..	..	..	..	..	271	4·6	1·7	117	SE/E	Var.	269	5·0	2·7	195	S	Var.
Hyderabad	..	..	..	..	..	..	151	6·0	5·0	114	E	SE	147	5·4	2·3	45	ENE	Var.
Waltair	184	4·3	2·7	68	E	NE	183	5·0	3·3	59	NE	E	179	5·3	2·8	36	N—E	
Mangalore	186	6·2	4·5	80	E	N	186	5·6	4·2	90	NW—NE—SE		186	6·0	4·7	92	NE—SE	
Bangalore*	..	..	..	..	..	..	381	5·4	4·8	91	..	..	368	6·0	4·9	75	NE—SE	
Madras	244	6·5	5·6	55	NE	E	237	6·6	5·9	63	NE	E	208	6·6	5·3	71	N—SE	
Port Blair	244	7·3	6·6	62	NE	E	211	7·5	6·9	85	E	NE	163	6·7	5·6	93	E	SE
Trivandrum	169	2·8	1·3	55	N—SE		168	3·6	2·3	57	N—SE		158	5·0	2·8	85	E	Var.

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—January.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
18	5·7	1·2	308	Var.		13	5·8	3·2	274	WNW		8	9·1	4·2	281	W	Var.	4	11·2	5·8	273	..	..
124	11·8	10·4	274	SW—NW		81	15·7	14·6	274	SW—NW		26	21·4	20·5	276	W		4	28·8	28·1	286	..	..
162	9·7	8·3	283	SW—NW		128	13·1	11·8	276	SW—NW		54	18·9	18·2	271	SW—NW		11	22·8	21·4	263	SW—N	
135	11·5	10·3	285	W	NW	101	15·5	14·4	282	W	NW	47	23·6	21·7	279	SW—NW		9	30·0	27·8	286	..	..
244	11·2	9·6	279	SW—NW		228	14·9	13·6	274	SW—NW		147	24·0	21·8	277	W	NW	35	33·0	27·8	282	W	NW
249	8·0	6·2	286	SW—NW		186	12·6	11·9	283	SW—NW		48	21·7	19·2	280	SW—NW		6	22·7	22·1	292	..	..
250	4·5	0·9	275	Var.		234	7·2	4·4	265	SW—NW		189	15·9	13·4	277	SW—NW		93	24·9	22·3	282	SW—NW	
351	6·4	3·8	255	S—NW		312	9·5	7·2	264	S—NW		231	18·5	16·5	274	SW—NW		122	28·1	25·1	279	SW—NW	
367	4·9	2·1	155	SSE	NW	334	6·9	2·7	230	Var.		220	16·5	14·6	221	SW—NW		115	28·6	26·7	270	SW—NW	
48	9·7	8·6	271	SW—NW		34	14·7	13·8	273	SW—N		3	27·0	25·5	269	..	..	1	23·0	23·0	255	..	..
165	9·9	7·6	265	SW—NW		139	12·8	11·1	268	SW—NW		85	20·1	16·0	273	SW—NW		22	24·2	22·8	272	SW—NW	
169	11·6	9·9	268	SW—NW		135	15·6	14·2	269	SW—NW		74	24·6	23·1	272	SW—NW		10	28·3	26·9	267	SW—NW	
485	10·3	9·0	273	SW—NW		452	14·4	13·0	272	SW—NW		339	23·9	22·0	273	SW—NW		172	31·6	29·9	274	SW—NW	
79	12·2	11·2	288	NW	W	47	13·8	13·0	285	W	NW	16	18·3	17·5	280	SW—NW		3	24·8	24·4	272	..	..
159	15·2	14·8	290	W	NW	127	18·4	17·0	289	W	NW	62	25·7	21·7	283	W	NW	5	24·7	24·4	294	..	..
29	17·0	16·1	285	W	NW	20	25·1	24·6	280	W	NW	4	27·7	27·3	261	..	..	..	..	..	..	..	..
104	7·7	4·7	271	NE/E	W	70	18·8	16·9	273	W	NW	18	23·0	20·1	273	W	NW	2	27·5	27·1	284	..	..
274	11·1	10·5	289	W	NW	233	14·5	13·6	279	SW—NW		119	19·2	17·8	271	SW—NW		24	26·5	25·7	270	W	SW
137	13·8	13·6	286	W	NW	105	18·5	17·9	278	SW—NW		36	25·0	23·7	274	SW—NW		5	27·9	26·3	264	..	..
141	11·7	10·7	281	W	NW	99	15·0	14·0	275	SW—NW		30	20·5	19·5	276	W	NW	5	22·3	21·9	270	..	..
316	9·0	7·9	280	SW—NW		300	11·9	10·9	275	SW—NW		222	17·1	16·2	270	SW—NW		73	22·0	20·4	268	SW—NW	
171	10·9	9·7	273	SW—NW		153	15·9	15·0	274	SW—NW		43	22·2	21·2	269	SW—NW		4	25·1	23·4	276	..	..
156	5·2	2·8	274	W	Var.	136	6·7	5·0	283	SW—N		94	9·4	7·8	270	SW—NW		20	13·0	12·0	252	SW	W
170	11·6	9·4	283	NW	W	138	13·8	12·7	280	W	NW	60	18·7	17·7	277	SW—NW		14	28·3	27·0	270	W	SW
32	14·6	13·9	291	NW	W	20	16·9	16·1	279	W	NW	1	25·0	25·0	260	..	..	..	..	..	..	..	..
111	8·7	7·3	302	SW—N		77	10·8	9·4	294	W	NW	57	17·2	15·3	267	SW—NW		25	27·5	26·6	271	SW—NW	
265	6·7	3·5	279	Var.		254	8·7	6·6	283	SW—N		220	12·5	10·7	261	SW—N		137	17·5	15·5	276	SW—N	
147	5·2	1·3	335	Var.		142	6·7	1·4	352	SW—N		122	9·2	6·8	279	SW—NW		80	14·8	13·1	267	SW—NW	
153	6·1	2·6	327	N	Var.	135	7·1	4·2	297	SW—N		92	10·1	8·4	274	SW—NW		27	15·7	15·1	257	W	SW
179	6·4	4·1	83	NNE	Var.	152	7·3	4·1	82	Var.		74	7·6	0·7	130	Var.		20	9·1	3·1	299	NNW	S
341	5·2	2·9	83	NE—SE		315	5·9	1·9	77	Var.		232	7·5	1·1	308	Var.		157	10·0	4·9	270	W	Var.
175	5·5	3·7	78	N—SE		153	5·7	3·1	74	Var.		103	6·4	0·7	332	Var.		47	9·0	4·6	278	WSW	Var.
120	4·9	3·8	85	NE—SE		98	4·9	3·3	89	N—SE		73	6·3	3·3	64	NE	Var.	45	6·9	2·0	S	NNE	Var.
141	5·9	3·6	94	ESE	Var.	120	7·8	5·5	91	E	Var.	80	9·9	6·6	89	ENE	Var.	19	9·7	2·9	100	E	Var.

for the remaining stations, data up to the end of 1934 have been used.

E

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	56	6·7	6·4	86	E		48	7·1	6·9	79	E	NE	35	4·7	2·9	142	E—S	
Bahrein	187	9·5	1·3	340	N/NW	S/SE	179	8·8	2·6	281	NNW	S/SW	146	9·1	6·7	267	S—NW	
Muscat	191	4·8	2·5	273	WNW	Var.	188	5·3	3·0	278	WNW	Var.	173	7·3	4·9	283	WNW	Var.
Gwador	187	5·4	2·2	304	W	Var.	182	5·7	2·6	296	W	Var.	158	7·1	4·9	287	W	Var.
Karachi*	254	7·3	3·3	337	W—N—E		248	6·7	3·4	304	WNW	Var.	242	7·1	4·7	287	WNW	Var.
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	260	4·4	1·8	237	S	NW
Peshawar*	243	2·2	0·3	22	..	..	242	3·0	2·1	326	W—N		233	4·8	2·2	324	NNW	Var.
Lahore*	359	5·6	2·5	342	NW	Var.	355	5·3	2·4	320	NW/N	Var.	339	5·7	3·1	291	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	55	6·5	2·0	302	NW/W	S/SE	56	6·0	2·7	291	NW	S	53	6·9	4·5	284	SW—NW	
Ahmedabad	164	7·6	3·4	33	E	NW	163	5·2	1·9	338	W—N—E		159	6·5	4·3	275	SW—NW—NE	
Ajmer	..	..	..	..	..	..	169	6·2	1·6	309	Var.		168	7·4	5·3	284	SW—N	
Agra*	486	6·5	3·0	338	NW/N	SE	484	6·5	4·1	308	NW	Var.	476	8·4	6·8	287	SW—NW	
Allahabad	112	6·0	1·5	329	NW	Var.	112	6·4	3·4	304	NW	Var.	101	9·2	7·7	289	NW	W
Patna	169	5·8	2·5	297	WNW	ESE	169	5·8	3·9	291	WNW	Var.	161	9·9	8·9	287	W	NW
Rangpur	55	4·7	1·2	336	Var.		54	4·0	1·5	293	W	Var.	52	6·7	4·8	282	WNW	Var.
Tezpur	134	5·1	2·8	99	E	Var.	131	4·4	0·4	206	ENE	WSW	118	6·2	3·9	248	W/SW	E
Calcutta*	292	5·7	2·4	315	N	Var.	281	5·6	3·6	299	SW—N		265	9·8	8·5	292	SW—NW	
Dacca	154	4·6	2·3	318	NNW	Var.	151	4·5	3·0	290	WNW	Var.	146	9·3	7·6	284	W	NW
Chittagong	164	4·6	2·9	356	N	Var.	163	4·3	2·7	328	N/NW	Var.	151	7·8	6·1	300	NW	W
Akyab*	296	5·4	4·4	351	N	NW	297	5·6	4·0	333	N/NW	Var.	291	7·5	5·4	305	SW—N	
Mandalay	169	4·0	2·2	168	S/SE	N	168	4·4	1·2	216	S/SW	N/NW	169	6·1	5·2	244	SW	W
Rangoon	165	4·0	1·5	305	Var.		168	3·7	1·3	226	Var.		167	5·3	3·1	232	SW	Var.
Jubbulpore	..	..	..	..	..	..	168	6·2	0·7	326	SSW	NNE	165	8·0	6·3	284	SW—N	
Ranchi	..	..	..	..	..	..	56	6·0	3·5	323	NW	Var.	55	8·5	7·3	284	SW—NW	
Sambalpur	110	4·5	0·4	99	Var.		110	5·2	2·7	280	Var.		111	8·2	6·9	284	SW—NW	
Poona*	..	..	..	..	N	E	251	5·0	1·4	50	E	Var.	251	6·0	2·2	210	S	Var.
Hyderabad	..	..	..	..	..	..	139	6·8	3·2	146	NE—SE—SW		138	5·4	1·1	309	Var.	
Waltair	164	4·0	1·2	239	SW	NE	165	3·8	0·6	197	SW	NE	153	5·3	2·6	347	NNE	Var.
Mangalore	168	4·2	1·7	9	NNW	E	168	4·3	1·3	57	NW	ESE	157	6·0	3·6	94	NE—S	
Bangalore*	..	..	..	..	..	..	367	4·9	3·7	111	..	..	355	6·1	4·4	70	N—SE	
Madras	224	4·7	2·9	118	NE—S		223	5·5	4·1	94	NE—SE		209	7·1	5·2	56	NE/E	Var.
Port Blair	221	5·3	4·4	52	N—E		207	5·0	3·4	80	N—SE		181	5·5	2·9	108	ESE	Var.
Trivandrum	153	2·4	0·8	49	Var.		154	2·9	1·2	81	ENE	Var.	145	4·9	3·0	69	ENE	Var.

*For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—February.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
33	4·6	1·1	98	N—E—S		31	6·9	2·5	28	ENE	NW	20	6·4	1·0	184	SW	Var.	8	6·3	2·3	298	..	..
110	12·1	10·4	269	SW—NW		66	15·2	13·8	276	SW—N		22	22·5	20·6	281	SW—NW		1	30·0	30·0	275	..	..
154	10·5	7·8	281	WNW	Var.	123	12·2	10·3	283	SW—NW—NE		51	17·7	16·0	279	SW—N		9	25·0	24·0	285	..	..
137	9·8	8·1	284	SW—NW		100	13·4	11·8	282	SW—N		45	19·7	18·4	285	W	NW	8	22·9	22·2	286	..	..
221	9·5	7·8	282	SW—N		197	13·0	11·4	282	SW—N		139	21·3	19·4	277	SW—N		37	28·7	27·6	278	SW—N	
238	8·5	6·7	278	S—NW		184	14·0	12·0	283	S—W—N		51	21·3	19·6	277	W	NW	14	23·1	21·4	275	W	
221	5·6	2·3	259	NW	Var.	198	7·7	5·1	271	WNW	Var.	168	16·2	13·6	277	S—W—N		95	24·7	21·8	277	S—W—N	
309	7·4	5·0	276	S—NW		270	10·5	8·3	276	S—NW		174	19·4	17·4	278	SW	W	88	29·6	29·4	282	SW—N	
355	5·4	0·8	254	SE/S	NW	323	7·6	3·8	279	SE—SW—NW		202	17·8	16·4	274	SW—NW		112	29·6	27·6	273	SW—NW	
44	8·7	7·1	275	SW—NW		38	12·1	10·8	278	SW—NW		23	20·4	19·4	276	SW—NW		7	26·2	25·1	271	..	..
148	9·5	7·5	270	SW—N		120	12·1	10·5	273	SW—N		62	18·5	17·4	275	SW—N		10	24·7	24·1	279	W	
154	9·4	7·7	275	SW—NW		125	13·0	11·4	276	SW—N		67	21·0	19·3	273	SW—NW		5	25·6	25·0	289	..	..
457	11·5	9·9	279	SW—NW		424	15·3	13·9	277	SW—NW		307	24·5	23·1	277	SW—NW		148	33·4	31·4	277	SW—NW	
62	11·8	11·1	278	W	NW	38	16·9	16·0	271	W	NW	2	32·5	32·3	265	..	..	..	..	..	..	..	..
127	13·5	12·7	288	W	NW	99	17·2	16·9	283	W	NW	45	24·7	23·8	278	SW—NW		7	33·0	30·5	290	..	..
47	11·5	9·8	280	SW—NW		35	15·4	13·7	288	W—N—E		15	19·4	18·0	278	SW—NW		..	..	..	..	..	..
92	7·9	6·4	260	W/SW	ENE	60	13·7	12·8	271	SW—NW		20	19·0	18·2	269	W	NW	2	18·5	18·3	288	..	..
222	13·0	12·0	291	SW—NW		174	15·1	13·8	289	SW—N		74	21·0	20·1	274	SW—N		3	23·8	23·5	279	..	..
114	12·7	11·8	283	SW—NW		73	16·0	15·3	280	W		21	23·9	23·6	270	SW—NW		..	..	..	..	..	..
129	11·7	10·6	288	W	NW	92	14·3	13·7	275	W	NW	20	24·2	23·2	270	SW—NW		..	..	..	..	..	..
283	9·5	8·1	285	SW—NW		264	12·5	11·3	279	SW—NW		180	19·3	17·9	274	SW—N		58	24·3	21·7	270	SW—NW	
153	9·9	8·8	262	SW—NW		124	15·1	14·3	273	SW—NW		32	22·9	21·9	274	SW—NW		1	36·5	36·5	260	..	..
153	6·3	4·6	253	S—NW		112	8·5	7·3	271	S—W—N		73	11·9	10·4	263	S—W—N		11	16·1	14·8	253	SW—NW	
152	11·8	10·1	278	SW—N		122	15·1	13·6	277	SW—N		44	20·7	19·8	281	W	NW	3	38·4	38·0	256	..	..
52	11·7	10·4	285	SW—NW		38	13·6	12·7	287	W	NW	17	18·9	17·8	288	W	NW	2	22·5	22·2	288	..	..
100	11·1	10·0	285	W	NW	76	14·1	13·5	285	W	NW	42	23·7	22·9	273	SW—NW		12	31·3	30·8	261	W	SW
246	7·4	3·4	249	SSW	Var.	233	9·4	6·5	284	SW—NW—NE		193	14·7	12·1	283	S—W—N		103	18·4	16·7	278	S—NW	
135	6·8	3·3	202	SW—N		131	8·4	5·9	286	WSW	ENE	106	13·0	10·6	284	SW—N		54	17·7	14·9	283	W	NW
140	7·1	4·9	316	Var.		118	8·6	6·7	292	SW—N		63	14·1	12·5	271	SW—NW		8	20·6	19·7	251	..	..
134	6·2	2·4	80	ENE	Var.	110	6·5	0·9	333	Var.		61	8·8	2·0	324	SW—NW—NE		10	10·9	3·9	299	..	..
337	6·1	3·4	63	ENE	Var.	306	6·3	1·6	62	ENE	Var.	256	7·7	1·4	329	Var.		180	9·0	4·1	294	Var.	
190	5·8	2·9	36	NE	Var.	169	5·4	1·3	15	NE	Var.	123	7·8	3·6	290	S—W—N		40	10·8	7·7	287	S—W—N	
161	5·4	1·4	97	E	Var.	149	5·4	0·4	54	E	Var.	116	6·6	1·9	288	WSW	Var.	57	8·1	2·7	255	S	Var.
134	5·9	3·7	85	ENE	Var.	102	7·1	4·0	96	ESE	Var.	63	9·5	6·3	110	ESE	Var.	20	10·2	6·9	115	E	SE

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	59	6·3	6·1	91	E		50	6·9	6·5	86	E		40	5·3	2·6	90	E	NE
Bahrein	209	9·2	2·3	351	N/NW	SSE	200	8·4	2·3	305	N/NW	S/SW	169	8·5	5·5	275	S—W—N	
Muscat	200	4·7	2·8	266	S—NW		198	5·1	3·2	270	W	Var.	183	6·8	4·5	278	SW—N	
Gwador	209	6·1	3·5	290	W	Var.	205	6·4	3·9	286	WNW	Var.	176	7·7	4·9	277	WNW	Var.
Karachi*	277	7·7	5·2	306	W—NE		276	7·3	4·9	296	WNW	Var.	267	7·4	5·2	281	W	Var.
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	295	4·2	1·8	258	WNW	S
Peshawar*	269	2·6	0·7	324	..	..	269	3·4	1·9	332	NW	N	263	5·1	2·7	310	NW	N
Lahore*	400	6·3	2·9	356	NNW	Var.	399	5·8	2·7	331	NW/N	Var.	387	6·3	3·8	299	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	62	7·4	4·9	330	NW	Var.	62	7·9	6·2	313	NW	Var.	60	9·5	8·4	301	NW	W
Ahmedabad	185	7·9	4·9	355	NW—E		186	5·7	3·4	334	W—N—E		185	6·1	4·1	268	SW—N	
Ajmer	..	..	..	..	..	..	182	6·1	2·6	303	Var.		184	7·5	5·6	279	SW—NW	
Agra*	559	6·9	2·6	335	NW	Var.	558	6·7	3·8	308	NW	Var.	549	8·6	6·9	289	NW	W
Allahabad	153	6·4	3·7	323	NW	Var.	153	6·5	4·8	305	NW	Var.	141	9·5	8·4	289	SW—NW	
Patna	162	7·7	3·8	310	NW	Var.	162	7·6	5·7	292	NW/W	SE	156	10·1	9·2	287	W	NW
Rangpur	59	6·0	2·2	120	ESE	Var.	54	5·0	1·6	226	E—S—W		48	7·3	4·5	266	W	Var.
Tezpur	144	6·3	4·0	94	E		144	5·2	1·2	193	E	Var.	130	7·1	6·3	251	W	SW
Calcutta*	324	6·9	4·3	251	SW	Var.	317	6·0	3·9	268	S—W—N		297	7·3	6·0	289	SW—N	
Dacca	152	5·7	3·3	254	WSW	Var.	140	5·5	3·6	267	S—NW		118	7·4	6·0	280	SW—NW	
Chittagong	177	4·5	1·2	257	SSW	Var.	168	4·7	2·0	287	Var.		152	6·6	4·6	302	S—W—N	
Akyab*	364	5·0	3·7	338	N	NW	356	5·5	4·6	329	SW—N		343	6·9	4·7	311	SW—N	
Mandalay	184	6·7	5·0	183	S	N	185	5·5	2·6	197	S/SW	N	182	5·4	3·8	265	SW—NW	
Rangoon	183	4·4	1·8	255	WNW	Var.	182	4·2	2·4	230	WSW	Var.	172	4·7	2·9	224	SW	Var.
Jubbulpore	..	..	..	..	..	..	182	5·8	1·1	31	NE	Var.	181	6·9	4·9	289	SW—N	
Ranchi	..	..	..	..	..	..	62	7·3	3·3	277	NW	Var.	61	7·9	7·1	289	SW—NW	
Sambalpur	120	4·3	0·7	18	SW	NNE	123	4·8	1·6	294	Var.		124	6·0	3·3	287	SW—N	
Poona*	..	..	..	..	..	..	278	5·3	2·8	11	NNE	Var.	276	5·7	0·8	277	Var.	
Hyderabad	..	..	..	..	..	..	154	6·7	3·3	311	S	Var.	152	5·3	1·7	104	Var.	
Waltair	177	4·9	4·5	233	SW	W	173	4·5	3·1	220	SE—W		161	5·0	1·8	8	Var.	
Mangalore	181	3·0	1·1	357	NNW	Var.	185	4·0	1·3	46	N	Var.	171	6·1	4·8	77	N—SE	
Bangalore*	..	..	..	..	..	..	392	4·3	2·0	159	..	..	419	6·8	5·6	79	NE—SE	
Madras	247	4·8	3·7	158	E—S		245	5·1	3·4	134	NE—S		237	7·4	5·9	57	N—E	
Port Blair	257	4·1	2·8	56	NW—NE		253	4·4	2·9	85	NW—NE—SW		234	5·2	3·6	93	N—SE	
Trivandrum	176	3·0	1·6	359	NW—E		174	3·2	1·4	21	NE—SE		172	5·0	3·0	63	NE—SE	

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—March.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
31	5·9	3·3	65	E	NE	26	6·1	3·9	48	N—E		18	6·6	2·9	260	W	Var.	9	8·2	4·7	278	..	..
124	10·2	8·4	268	SW—N		67	12·2	10·1	280	SW—N		28	16·9	13·6	273	SW—N		11	21·4	18·0	270	W	SW
161	8·9	6·8	285	SW—NW		123	10·2	8·6	283	S—NW		65	14·6	12·8	279	SW—NW		12	24·8	23·3	279	W	NW
133	9·8	7·7	285	WNW	Var.	89	10·6	9·1	284	SW—N		54	17·3	15·8	285	SW—N		10	21·6	21·2	282	W	
241	9·5	6·8	278	W	Var.	208	11·3	9·5	276	SW—N		144	17·8	16·3	275	SW—N		37	27·0	25·3	277	SW—NW	
288	7·8	5·9	283	SW—NW		242	11·3	9·5	284	S—W—N		90	14·9	13·5	282	SW—N		25	16·0	15·0	279	SW—NW—NE	
255	6·6	3·8	277	WNW	Var.	233	8·0	5·4	276	S—W—N		207	14·1	11·6	281	W	Var.	109	19·9	16·7	281	SW—NW	
368	7·9	5·7	288	NW/W	Var.	340	9·9	7·7	282	S—W—N		233	15·8	13·9	278	SW—NW		136	20·2	18·4	281	SW—NW	
397	5·4	1·8	291	NW	Var.	361	6·9	3·9	288	NW	Var.	248	13·9	12·0	279	S—W—N		157	22·0	19·6	272	SW—N	
53	10·5	9·3	292	NW	W	36	12·1	10·6	283	SW—NW		11	18·5	16·7	269	SW—NW		1	14·5	14·5	320	..	..
175	8·8	6·6	252	S—NW		141	9·9	7·6	255	S—W—N		96	13·3	11·7	274	SW—N		24	16·3	14·2	284	SW—N	
167	9·4	7·4	269	S—NW		129	11·5	9·7	269	SW—N		68	15·7	13·9	277	SW—NW		15	17·0	13·9	271	SW—N	
522	10·9	9·4	285	SW—NW		478	13·2	11·4	280	SW—N		366	18·9	17·1	276	SW—N		189	24·9	23·3	278	SW—N	
93	12·3	11·1	282	W	NW	55	14·2	13·1	279	W—N		23	16·2	13·0	281	W—N		4	18·7	18·5	276	..	..
136	13·7	12·5	286	W	NW	99	15·7	14·7	291	SW—N		46	17·2	16·1	287	NW	W	14	19·6	17·9	287	SW—NW	
40	10·3	7·3	274	W	Var.	29	12·0	10·2	289	W	NW	11	12·9	11·2	287	SW—N		..	..	..	..	..	..
113	10·2	8·9	260	W	SW	62	12·1	10·4	272	S—W		21	16·4	15·0	276	W		5	22·3	19·7	283	..	..
270	10·4	9·3	293	NW	W	225	11·7	10·8	292	SW—NW		138	15·6	14·5	278	SW—N		34	18·1	16·1	274	W—N	
84	10·6	9·4	288	W	NW	61	12·4	11·1	291	W	NW	30	15·0	13·5	273	W—N		7	17·1	15·8	275	..	..
116	8·7	6·9	297	SW—N		79	9·3	8·0	283	SW—NW		29	13·8	12·9	279	SW—NW		3	18·0	12·9	309	..	..
327	8·2	5·8	297	SW—N		295	9·5	8·1	282	SW—N		204	14·7	13·6	271	SW—NW		78	20·8	19·3	266	SW—NW	
156	7·7	6·5	259	SW—NW		117	11·1	9·8	274	SW—NW		38	17·2	15·6	277	W	NW	1	7·0	7·0	285	..	..
154	5·2	2·7	238	SW	Var.	114	6·3	4·4	259	S—NW		63	9·6	7·9	267	S—NW		15	12·2	10·3	277	..	..
169	10·2	8·3	277	SW—N		146	11·8	10·1	278	SW—N		77	15·0	13·7	281	SW—NW		12	18·3	17·4	267	..	..
53	12·2	10·8	295	SW—N		43	12·2	11·1	302	W—N		19	14·2	13·2	293	SW—NW		4	17·4	17·2	270	..	..
114	8·4	6·8	294	W—N		90	10·0	8·8	295	W—N		58	14·6	13·4	277	SW—N		24	21·2	19·7	276	W	
268	5·9	2·8	197	SSW	Var.	261	6·7	3·2	249	SW	Var.	229	11·0	8·8	283	SW—NW—NE		147	16·1	14·1	274	SW—NW	
149	5·1	2·1	359	Var.		142	5·6	2·4	321	SW—N		119	19·8	8·2	271	SW—N		73	14·7	13·2	264	SW—NW	
145	5·6	3·4	11	NNE	Var.	112	6·4	3·4	340	SW—NW—NE		74	8·8	6·9	267	WSW	N	22	11·7	9·9	257	SW—N	
149	6·8	5·5	69	NE	N	107	6·8	3·7	71	N—E		63	5·9	1·2	301	W—N—E		18	9·6	4·4	279	..	..
400	8·1	7·1	54	N—E		367	7·2	4·9	66	ENE	Var.	290	6·8	0·5	18	Var.		206	9·9	3·7	286	W	Var.
223	7·1	4·9	51	N—E		200	5·5	3·1	59	N—SE		145	6·1	0·7	61	ENE	Var.	47	7·2	0·5	341	NW	Var.
202	5·0	3·0	95	E	Var.	173	5·0	2·1	101	ESE	Var.	131	6·6	2·3	90	ESE	Var.	59	7·3	2·3	79	Var.	
154	6·3	3·6	83	NE—SE		114	7·2	4·6	104	E	Var.	41	8·0	5·2	102	ESE	Var.	10	5·9	2·0	125	ESE	W

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	59	5·8	5·4	87	E		44	6·2	5·3	87	E	NE	36	4·5	2·2	108	NE—S	
Bahrein	202	8·5	3·5	347	NNW	S	196	7·9	3·5	312	NNW	SW	179	8·6	5·4	273	S—W—N	
Muscat	209	5·1	3·9	266	SW—NW		208	5·8	4·5	276	SW—NW		203	6·6	4·9	289	SW—N	
Gwalior	207	6·9	5·2	287	SW—NW—NE		203	7·5	5·5	298	SW—N		176	7·7	6·3	287	SW—N	
Karachi*	269	9·5	8·3	293	W—NE		264	9·5	7·9	293	W—N		253	8·3	6·6	286	SW—N	
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	286	4·2	1·7	246	S	WNW
Peshawar*	260	2·8	1·1	324	..	..	260	3·8	2·2	341	NW—NE		259	4·7	2·7	322	NNW	Var.
Lahore*	410	6·8	3·2	3	NNW	Var.	411	5·9	2·3	339	NNW	Var.	405	6·1	3·5	303	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	58	7·7	4·9	324	NW	Var.	59	7·6	5·7	311	NW	Var.	55	8·9	7·8	294	NW	W
Ahmedabad	178	8·9	6·3	317	NW	Var.	177	6·9	4·5	307	W—NE		172	6·4	4·8	262	W	Var.
Ajmer	..	..	..	..	..	..	180	7·2	3·8	278	W	Var.	178	8·1	6·5	278	SW—N	
Agra*	534	7·2	3·2	332	NW	Var.	534	6·7	3·9	312	NW	Var.	519	7·9	6·7	292	SW—N	
Allahabad	149	6·8	4·0	304	NW	Var.	149	6·7	5·1	302	NW	Var.	131	8·2	7·4	295	NW	W
Patna	150	8·1	2·6	287	NW/W	SSE	149	7·6	5·2	286	SE—SW—NW		143	9·9	9·4	288	W	NW
Rangpur	49	6·9	2·8	165	SE	Var.	39	6·6	3·6	250	WSW	Var.	29	7·5	5·8	265	SW—NW	
Tezpur	126	8·1	5·5	96	E	SW	121	5·5	1·5	163	ESE	WSW	100	8·4	7·7	250	W	SW
Calcutta*	341	7·7	6·9	221	S—W		320	7·4	5·3	248	S—W—N		265	6·5	5·3	282	SW—NW	
Dacca	153	8·2	6·4	208	SE—SW—NW		119	7·5	6·0	232	S—NW		94	7·9	6·2	266	S—NW	
Chittagong	177	6·5	5·1	196	S	SW	158	6·0	4·3	220	SW	Var.	134	6·6	5·1	275	SW—N	
Akyab*	346	4·0	1·8	277	S—W—N		339	4·3	2·7	294	S—W—N		316	6·2	4·4	305	SW—N	
Mandalay	180	8·7	7·6	182	S		180	7·8	6·3	192	S/SW	N	168	6·2	4·6	254	S—W—N	
Rangoon	178	5·8	4·6	269	W	Var.	171	5·1	3·8	239	SW	Var.	162	4·5	2·7	233	SE—SW—NE	
Jubbulpore	..	..	..	..	..	..	179	6·7	2·6	309	Var.		178	6·7	5·2	293	SW—N	
Ranchi	..	..	..	..	..	..	54	6·7	4·3	285	S—W—N		54	7·8	6·7	287	SW—NW	
Sambalpur	118	4·9	2·0	226	SW	NNE	118	6·2	1·9	278	WSW	Var.	119	6·1	5·0	291	SW—N	
Poona*	..	..	..	..	..	..	246	6·1	4·2	334	W—NE		243	6·6	2·3	318	Var.	
Hyderabad	..	..	..	..	..	..	148	8·0	2·4	214	S	Var.	148	4·9	0·6	133	Var.	
Waltair	179	7·4	6·9	238	SW	W	172	6·2	5·1	237	S—W		161	4·1	1·1	332	Var.	
Mangalore	176	3·6	2·6	308	NNW	Var.	176	3·6	1·8	325	NNW	Var.	158	4·8	3·1	46	NW—NE—SE	
Bangalore*	..	..	..	..	..	..	383	4·0	2·2	236	..	..	389	5·1	3·1	80	NW—NE—SE	
Madras	262	7·2	6·2	197	SE—SW		261	5·3	3·9	188	SE—SW		253	5·9	4·6	80	NE—SE	
Port Blair	268	3·6	0·4	354	Var.		262	3·7	0·7	126	Var.		246	4·9	2·5	92	E	Var.
Trivandrum	173	4·7	3·8	333	W—NE		172	4·9	3·4	333	NW	Var.	153	5·3	2·9	34	NW—E	

* For stations marked with an asterisk the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—April.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
31	6·2	3·5	81	NE—SE		28	6·5	5·3	50	NE	E	17	6·7	0·3	104	Var.		9	10·0	6·1	301	..	..
142	9·9	6·9	264	W	Var.	92	10·5	7·7	265	W	Var.	36	11·7	5·7	265	W	Var.	15	15·6	8·2	279	S—W—N	
187	8·6	5·4	296	WNW	Var.	134	8·9	5·1	299	Var.		73	9·6	7·2	280	SW—N		20	13·0	10·5	280	SW—NW	
148	8·3	5·8	284	WNW	Var.	101	8·2	4·6	282	Var.		64	10·1	7·9	275	SW—N		17	13·3	11·6	276	SW—N	
231	8·6	5·7	286	WNW	Var.	197	9·3	6·0	289	SW—NW—NE		136	12·2	10·2	276	SW—N		37	17·6	15·8	286	SW—N	
281	7·3	5·2	287	S—NW		240	9·7	7·5	290	SW—N		103	12·1	10·1	270	SW—N		36	18·9	15·5	267	SW—N	
256	6·5	3·7	274	SE—SW—NW		243	8·1	5·2	273	S—NW		194	11·4	8·8	280	WNW	Var.	107	15·8	13·0	284	WNW	Var.
385	8·1	5·3	291	NW	Var.	356	9·4	6·9	278	S—W—N		266	19·9	10·7	281	SW—N		175	17·2	15·1	281	SW—N	
420	5·9	2·7	306	NW	SSE	379	6·9	4·1	293	S—NW		268	11·5	9·2	275	S—NW		174	16·5	14·5	272	SW—NW	
46	9·2	7·4	289	SW—NW		33	9·9	8·8	282	SW—NW		19	13·4	11·7	276	SW—NW		6	18·0	16·8	295	..	..
160	8·5	6·7	254	WSW	Var.	135	9·6	7·7	253	S—W—N		70	11·0	9·6	279	S—W—N		16	17·5	14·2	281	SW—NW	
155	8·9	7·2	273	SW—N		117	10·2	7·8	273	S—W—N		60	12·6	10·6	269	SW—NW		12	14·2	12·2	276	SW—NW	
493	10·3	8·6	286	SW—NW		448	11·8	10·0	279	SW—N		344	15·7	14·1	276	SW—NW		196	20·7	18·9	278	SW—N	
90	10·3	9·4	285	W	NW	58	12·5	11·7	282	W	NW	19	15·5	14·3	284	SW—NW		3	18·7	16·4	276	..	..
117	12·5	11·8	289	W	NW	84	13·8	13·0	289	W	NW	41	13·8	12·6	287	W—N		16	14·2	12·2	284	W—N	
21	11·5	8·8	278	SW—NW		15	12·2	8·9	291	WNW	E	6	14·5	4·6	342	..	..	..	..	..	..	.	..
62	10·7	10·4	262	W	SW	36	11·4	10·9	264	W	SW	7	12·9	11·6	265	..	..	1	25·5	25·5	280	..	..
220	9·3	8·3	292	W	NW	175	12·3	11·2	295	SW—N		111	14·2	11·8	283	SW—N		24	16·5	14·7	278	SW—NW	
68	10·0	9·1	283	SW—NW		50	13·0	11·9	284	W	NW	15	14·2	13·3	268	SW—NW		..	..	..	..	..	..
93	9·1	7·7	298	SW—N		61	9·7	8·5	295	SW—NW		12	12·5	10·2	278	SW—N		2	16·3	16·1	283	..	..
289	7·5	5·9	310	SW—N		241	8·4	6·7	306	SW—N		130	11·6	10·4	278	SW—N		40	18·2	15·5	273	SW—N	
132	8·2	7·1	268	SW—NW		89	9·8	9·0	279	SW—NW		26	14·0	13·1	280	W	NW	..	..	..	..	..	..
141	5·0	2·2	264	WSW	Var.	115	5·6	2·9	265	Var.		73	7·3	6·0	274	SW—NW		10	10·9	9·2	264	SW—NW	
166	8·4	7·5	282	SW—NW		145	10·2	8·9	277	SW—NW		76	11·8	10·4	286	SW—N		12	15·8	15·1	287	..	..
47	10·1	8·9	279	SW—NW		36	11·7	10·7	276	W	NW	13	12·7	10·6	286	SW—N		5	18·0	16·7	292	..	..
106	7·3	6·3	293	SW—N		81	9·3	8·2	302	W—N		39	9·6	8·6	295	SW—NW		11	14·4	13·4	275	SW—NW	
236	6·2	2·9	186	Var.		230	6·5	3·5	200	SW	S	198	9·4	5·6	289	W	Var.	126	12·6	8·9	277	W	Var.
144	5·2	2·9	32	NE	Var.	135	5·9	3·7	25	NE	N	94	7·4	4·4	299	W	Var.	59	10·9	8·3	282	W	Var.
135	5·3	3·2	15	Var.		105	6·3	3·9	5	NE	N	57	7·4	4·9	288	SW—NW		10	12·4	6·9	281	SW—NW—NE	
125	7·4	6·2	70	E	NE	87	7·9	6·5	67	NE—SE		33	7·5	4·2	38	NE/E	WSW	2	4·5	3·2	39	..	..
361	8·1	7·3	62	NE	E	312	8·1	6·4	58	NE	E	210	6·5	1·0	257	Var.		139	7·0	1·5	275	Var.	
232	8·1	6·9	49	N—E		211	7·5	5·7	42	N—E		159	5·9	2·1	62	Var.		51	7·6	0·8	302	Var.	
223	5·1	2·8	91	E	Var.	199	4·8	1·9	96	E	Var.	150	6·2	2·0	68	E	Var.	78	7·5	1·8	74	Var.	
127	7·5	5·0	56	ENE	Var.	89	7·9	4·8	68	E	Var.	30	8·5	4·2	45	NE	Var.	4	13·3	12·7	73	..	..

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	51	3·7	2·6	94	ENE	Var.	50	4·3	2·8	83	ENE	Var.	48	5·2	3·6	96	ESE	WNW
Bahrein	208	8·6	6·3	348	N	Var.	201	8·2	5·8	333	NNW	Var.	180	8·8	6·4	306	SW—N	
Muscat	212	6·0	5·2	269	SW—NW		214	7·0	6·5	283	SW—NW		210	6·9	5·5	295	NW	W
Gwador	210	7·3	5·7	278	W	Var.	202	8·1	6·4	291	WNW	Var.	163	7·1	6·0	292	SW—N	
Karachi*	277	9·9	9·3	281	W	NW	252	10·1	9·0	290	W	NW	220	7·8	6·5	292	SW—N	
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	204	4·2	2·1	276	WNW	S
Peshawar*	246	2·9	1·1	353	..	..	246	4·1	2·8	334	NNW	Var.	246	5·2	3·5	314	NW	Var.
Lahore*	417	6·6	2·0	20	NNW	Var.	416	6·0	1·6	340	NNW	Var.	399	5·8	2·7	294	S—W—N	
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	62	8·4	2·8	291	WNW	ESE	61	7·8	4·5	301	NW/W	ESE	58	7·7	6·6	301	SW—N	
Ahmedabad	195	8·5	5·7	284	SW—NW		187	7·9	6·3	284	W	NW	174	6·8	5·2	265	S—W—N	
Ajmer	..	..	..	..	..	..	216	8·8	7·0	266	W	Var.	206	8·4	6·7	281	SW—NW—NE	
Agra*	549	8·1	3·6	297	NW	Var.	545	7·5	4·6	300	NW	Var.	509	7·3	5·8	296	NW	W
Allahabad	154	7·0	1·7	318	NW	Var.	155	6·0	3·3	301	NW	Var.	133	7·6	6·5	299	NW	W
Patna	185	7·3	2·7	131	SE	Var.	184	6·4	2·4	252	Var.		176	8·9	7·6	294	NW	W
Rangpur	47	6·4	4·3	125	NE—SE—SW		88	4·9	2·3	185	E—S—W		32	6·2	2·7	257	W/SW	ESE
Tezpur	132	5·5	3·5	94	E	Var.	121	5·0	1·3	108	E	WSW	94	6·3	2·9	251	WSW	E/NE
Calcutta*	368	8·9	7·9	208	SE—SW		325	7·5	5·8	227	S—W		269	5·6	3·7	287	S—W—N	
Dacca	161	8·0	6·9	185	SE—SW		123	8·2	6·5	206	E—S—W		83	7·4	4·7	252	WSW	Var.
Chittagong	174	7·1	6·0	190	SE—SW		157	6·6	5·6	204	SW	S	124	6·1	3·9	250	WSW	Var.
Akyab*	333	4·2	1·5	234	Var.		320	4·3	1·9	260	SW	Var.	294	5·1	2·7	290	Var.	
Mandalay	182	8·9	8·2	181	S		180	8·1	7·6	189	S		166	6·0	4·4	243	S—W—N	
Rangoon	181	7·3	5·0	262	SE—SW—NW		171	6·3	4·3	254	SE—SW—NW		148	5·1	2·5	241	S	Var.
Jubbulpore	..	..	..	..	..	..	186	8·4	4·8	300	NW/W	Var.	183	7·2	6·1	307	SW—N	
Ranchi	..	..	..	..	..	..	61	5·6	2·5	255	NW	Var.	61	7·1	5·6	316	NW	Var.
Sambalpur	116	5·5	3·4	208	SW/S	Var.	118	6·7	4·0	257	SW	Var.	118	6·6	5·0	301	SW—NW—NE	
Poona*	..	..	..	..	..	..	275	7·2	6·1	301	W—N		256	6·9	4·3	326	NNW	Var.
Hyderabad	..	..	..	..	..	..	151	9·2	5·2	297	NW	Var.	152	6·2	1·7	328	N	Var.
Waltair	182	8·6	7·7	240	SW	W	175	7·6	6·2	243	SW	W	156	4·7	2·1	331	NW	Var.
Mangalore	185	5·2	3·7	306	W—N		171	5·0	3·5	308	SW—N		135	5·8	3·1	13	N	Var.
Bangalore*	..	..	..	..	..	..	421	5·5	4·7	278	SW—N		403	5·5	3·0	352	N	Var.
Madras	278	9·2	6·7	237	S—NW		277	7·1	4·1	246	SE—SW—NW		272	5·2	2·1	28	Var.	
Port Blair	256	7·5	5·3	237	WSW	Var.	236	6·7	4·3	233	WSW	Var.	192	4·7	0·9	186	Var.	
Trivandrum	163	6·2	5·2	309	W—N		162	7·1	6·0	306	W—N		130	6·7	4·3	330	W—N—E	

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—May.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
43	7·8	3·3	80	NE—SE		35	10·1	9·6	53	NE		20	9·0	6·9	71	E	NE	4	8·7	2·7	125	..	..
147	10·1	7·5	291	SW—N		87	10·6	7·4	291	NNW	Var.	35	9·3	6·0	287	S—W—N		19	11·9	9·7	269	S—W—N	
183	7·6	4·3	294	WNW	Var.	143	7·3	2·2	302	WNW	E	102	8·4	4·5	275	W	Var.	32	16·1	14·5	280	S—NW	
128	6·0	3·5	292	WNW	Var.	96	6·3	2·2	299	W	Var.	72	10·7	7·7	280	SW—N		15	14·3	12·6	257	WSW	N
176	6·3	4·5	304	NW/W	Var.	145	7·1	3·7	323	NNW	Var.	103	10·7	7·7	292	S—W—N		39	14·6	13·3	277	SW—NW	
295	8·3	7·3	299	NW	Var.	251	11·0	9·7	298	W	NW	110	11·1	8·5	298	S—W—N		52	12·8	9·7	301	SW—N	
243	6·5	4·0	292	NW/W	Var.	227	7·9	4·8	264	S—W—N		195	11·3	8·6	279	W	Var.	106	13·3	11·0	282	SW—N	
371	7·4	4·8	294	SW—N		336	9·4	6·6	294	NW	Var.	248	11·7	9·4	286	SW—NW		158	15·6	13·4	285	WNW	Var.
460	6·3	2·9	303	NW/W	SSE	404	7·7	3·7	298	SE—SW—NW		272	10·1	6·4	274	NWW	Var.	183	14·2	11·3	271	W	Var.
46	10·2	8·8	298	SW—NW		27	12·1	10·0	305	W—N		12	9·5	8·7	302	W—N		5	12·9	12·0	297	..	..
150	6·8	3·7	268	W	Var.	121	7·2	4·1	269	SW—N		86	8·7	6·1	299	SW—NW—NE		24	12·4	10·0	289	SW—N	
170	7·9	5·4	294	NW	Var.	119	8·9	5·7	301	SW—N		63	12·6	9·1	296	SW—NW—NE		10	16·6	14·7	292	NWW	S
453	9·0	7·1	293	NW	W	382	9·9	7·8	287	S—W—N		265	11·9	8·8	283	SW—N		163	14·7	11·3	276	S—W—N	
103	10·1	6·6	291	NW	W	69	12·2	9·9	293	SW—NW		23	13·3	11·8	285	NW	W	12	17·3	14·7	276	NW	W
142	12·5	11·3	299	NW	W	96	12·7	11·9	299	NW	Var.	48	13·0	10·6	296	NW	Var.	18	14·1	11·8	279	SW—N	
25	9·2	4·7	288	W	E	19	9·6	4·1	311	WNW	E	10	8·3	2·7	301	W	ENE	4	10·5	8·7	264	..	..
52	6·6	4·1	256	WSW	ENE	34	5·6	2·8	271	WSW	E	18	7·9	4·4	273	W		4	13·0	10·4	252	..	..
227	7·9	6·3	313	W—N		174	10·6	9·2	313	SW—N		96	8·8	6·6	287	SW—N		42	9·0	5·9	260	WSW	Var.
56	8·7	6·4	290	WNW	Var.	33	8·8	5·8	297	NW	SSE	17	7·7	3·7	289	W	Var.	4	3·3	1·5	269	..	..
80	7·5	5·6	298	SW—N		47	7·5	6·1	299	SW—N		21	7·8	5·6	268	NW/W	S	5	6·2	1·9	308	..	..
248	6·1	3·4	315	NW	Var.	214	7·1	4·6	308	SW—N		112	8·4	5·6	280	S—W—N		45	11·2	8·1	268	SW—N	
129	6·9	5·4	271	S—W—N		93	7·7	6·4	276	SW—NW		29	7·2	5·2	266	SW—NW		7	4·3	3·7	240	..	..
121	5·2	1·2	305	NW	Var.	83	4·9	0·9	310	SW	NNE	46	6·9	1·9	277	Var.		6	9·2	3·2	23	..	..
169	7·8	6·3	302	WNW	Var.	146	8·8	6·7	291	SW—N		67	10·1	7·9	298	SW—N		13	13·4	12·7	271	W	
55	10·3	8·6	308	NW	Var.	38	13·2	11·1	301	W—NE		21	13·1	11·1	296	SW—N		4	16·6	13·5	287	..	..
106	7·8	5·9	306	W—N—E		72	8·9	7·3	314	W—N		28	7·1	4·9	301	W—N		8	12·4	10·5	299	..	..
242	5·5	1·2	221	SSW	Var.	225	5·9	2·1	190	SSW	Var.	179	7·1	4·2	30	NNW	Var.	121	8·7	5·1	300	SW—N	
150	5·4	3·3	34	NE	Var.	137	6·7	4·5	45	NE	Var.	87	6·5	3·4	12	W—N—E		48	7·8	3·6	332	SW—NW—NE	
129	5·9	3·9	8	N	Var.	97	7·1	4·9	10	NW—NE		46	7·3	4·4	359	SW—NW—NE		8	9·7	5·4	21	..	..
104	6·7	5·0	65	E	NE	75	8·7	7·2	78	E		38	5·7	1·5	31	NE—S		5	7·2	2·5	333	..	..
351	6·6	5·0	59	NE	Var.	804	8·1	6·3	63	NE	E	192	5·5	2·2	46	E	Var.	117	6·3	2·1	26	Var.	
253	7·4	5·8	41	NE	Var.	232	8·5	6·5	42	NE	Var.	168	6·8	4·2	61	Var.		67	7·1	3·3	58	NE	Var.
150	4·9	1·2	92	ESE	Var.	118	5·1	0·5	187	Var.		72	5·1	1·1	192	S	Var.	28	5·9	1·5	289	W	Var.
90	8·9	4·0	18	NE	Var.	53	9·4	2·9	20	WNW	Var.	15	9·2	3·3	43	NNW	ESE	3	6·8	4·3	129	..	..

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	57	4·9	3·2	203	SSW	Var.	55	5·6	3·3	214	SSW	Var.	53	4·0	0·4	67	Var.	
Bahrein	195	14·0	13·0	344	N	NW	155	12·0	11·1	343	W—NE		117	9·7	8·1	336	N	NW
Muscat	209	4·6	3·3	282	WNW	Var.	209	6·1	4·6	297	W—NE		202	6·8	4·4	327	NNW	Var.
Gwador	193	4·4	1·9	244	W	Var.	165	5·6	2·7	300	WNW	Var.	126	7·0	4·2	328	W—N—E	
Karachi*	268	9·6	8·9	265	SW—NW		211	9·3	7·9	272	W	Var.	154	6·8	3·8	297	WNW	Var.
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	308	3·6	1·6	246	S	WNW
Peshawar*	240	3·4	1·8	346	..	..	240	4·0	2·5	330	NNW	Var.	240	5·1	3·5	301	NW	Var.
Lahore*	375	6·5	1·3	202	Var.		368	5·4	1·9	265	WNW	Var.	336	4·6	2·9	302	WNW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	59	9·6	3·0	296	NW	Var.	58	9·8	4·3	303	NW	SSE	50	7·7	5·4	305	NW	SE
Ahmedabad	205	8·4	7·4	248	WSW	Var.	194	8·7	7·7	254	WSW	Var.	159	6·5	3·4	245	SW	Var.
Ajmer	..	..	..	..	..	..	207	9·7	8·7	262	W	Var.	181	6·6	4·0	287	WNW	Var.
Agra*	528	8·0	3·4	273	WNW	Var.	529	7·7	4·4	292	WNW	Var.	477	7·0	5·0	314	W—N—E	
Allahabad	149	7·5	2·5	275	W	Var.	147	7·8	3·7	292	WNW	Var.	116	7·6	4·2	313	NW	Var.
Patna	177	7·3	3·4	125	SE	Var.	170	6·6	1·5	180	SE	Var.	155	7·2	2·9	299	WNW	Var.
Rangpur	45	6·7	4·3	130	NE—SE—SW		32	6·5	2·9	129	ESE	Var.	21	6·8	1·0	264	E	WNW
Tezpur	119	4·9	1·3	175	E—S—W		104	5·0	0·9	253	E—S—W		82	7·0	4·3	240	WSW	E
Calcutta*	351	8·5	6·6	208	SW	S	307	7·8	5·1	224	SW	Var.	222	6·3	2·8	278	W	Var.
Dacca	145	8·2	2·5	179	E—SW		97	7·1	5·2	182	E—S—W		66	6·6	1·5	231	S	Var.
Chittagong	155	9·6	9·0	171	SE—SW		128	8·8	8·2	179	SE—SW		87	7·6	5·3	102	SE—SW—NW	
Akyab*	253	6·6	5·0	185	SE—SW		208	6·7	4·5	203	S	Var.	135	6·7	1·7	227	SSW	Var.
Mandalay	178	11·3	11·1	180	S		176	12·0	11·9	185	S		147	7·5	6·5	211	SE—W	
Rangoon	175	8·1	6·9	217	SE—W		151	8·4	7·1	230	SE—W		94	8·2	6·8	229	S—W	
Jubbulpore	..	..	..	..	..	..	174	9·1	7·5	279	S—W—N		158	7·3	5·5	313	NW	Var.
Ranchi	..	..	..	..	..	..	58	8·4	4·1	246	S—NW		52	8·2	3·8	287	S—W—N	
Sambalpur	129	5·9	4·1	228	SW	Var.	122	7·6	5·6	264	WSW	Var.	106	7·8	5·2	300	WNW	Var.
Poona*	..	..	..	..	..	..	278	7·8	7·0	264	SW—NW		197	6·8	3·5	283	W	Var.
Hyderabad	..	..	..	..	..	..	147	12·5	11·4	284	W	NW	129	8·3	6·5	297	SW—N	
Waltair	175	9·8	8·7	252	W	SW	165	10·0	8·8	266	SW—N		135	7·2	5·7	293	SW—NW—NE	
Mangalore	176	6·9	5·6	263	S—NW		136	9·1	8·1	274	S—NW		63	8·4	6·9	277	SW—N	
Bangalore*	..	..	..	..	..	..	359	8·2	7·8	264	..	..	230	9·3	8·0	279	SW—N	
Madras	269	12·1	11·4	268	SW—NW		267	12·1	11·4	281	SW—NW		262	8·0	7·2	281	SW—N	
Port Blair	257	11·7	11·2	237	S—W		201	11·7	11·1	242	S—NW		130	8·9	7·9	244	SE—SW—NW	
Trivandrum	136	7·8	6·8	299	W—N		128	10·2	9·4	296	SW—N		76	12·2	10·3	307	W—N	

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used;

8 km. above Sea Level over India—June.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
50	6·5	3·4	44	W—N—E		47	9·2	8·1	36	NE	N	25	13·0	12·1	43	NE		8	9·0	7·9	60	..	..
75	8·5	4·7	344	N	Var.	52	9·0	3·0	21	NNW	Var.	24	6·6	1·9	19	Var.		14	8·5	1·5	295	W	ENE
174	6·5	2·1	17	NNE	Var.	139	7·8	4·5	62	ENE	Var.	76	8·2	5·6	34	NW—E		19	7·1	3·6	28	N	Var.
93	7·4	4·5	11	N	Var.	63	7·9	5·6	34	NW—E		27	9·5	5·2	29	Var.		6	6·4	3·3	23	..	..
117	6·3	3·2	19	NE	Var.	97	8·0	5·9	36	NE	Var.	57	0·3	1·5	3	SW	Var.	24	9·7	5·4	258	WSW	Var.
306	6·6	5·6	304	SW—N		280	8·0	6·7	303	SW—N		150	10·3	6·6	308	SW—NW—NE		68	14·0	11·0	287	SW—NW—NE	
237	5·6	3·8	296	S—W—N		227	6·4	4·7	287	S—W—N		178	9·9	8·1	292	SW—NW—NE		73	12·3	9·6	297	SW—NW—NE	
281	5·6	4·2	316	NW	Var.	249	7·2	5·8	320	W—N		166	8·6	6·6	303	SW—N		112	13·8	11·4	268	SW—NW	
400	6·6	1·3	308	NW	SE	315	6·7	3·9	312	NW	SE	200	7·2	4·3	277	SE—SW—NW		134	13·6	8·9	263	W	Var.
29	7·1	4·5	314	NW	Var.	17	7·0	5·2	353	NNW	E	8	10·8	9·2	318	..	..	3	20·3	18·5	300	..	..
117	6·0	1·0	09	Var.		92	7·1	2·7	64	NE	Var.	55	6·7	1·7	343	Var.		22	7·0	2·3	300	SW—N	
147	6·6	2·4	332	Var.		112	7·7	3·3	343	N	Var.	70	9·5	4·9	337	SW—NW—NE		18	13·5	10·0	311	W—N	
394	7·4	5·3	319	SW—NW—NE		333	7·9	5·2	322	SW—NW—NE		242	7·7	3·8	284	W	Var.	161	16·4	4·1	267	W	Var.
76	8·1	4·3	320	NW	Var.	44	8·4	3·9	323	WNW	ENE	18	10·1	3·0	250	WSW	ENE	10	12·4	4·5	270	W—N—E	
130	8·8	5·4	306	NW	Var.	98	8·3	4·6	292	WNW	Var.	58	6·6	2·4	260	WSW	Var.	31	8·0	4·6	244	SE—SW—NW	
11	6·5	3·7	86	E	W	7	6·5	2·9	74	..	..	2	5·7	1·6	115	..	..	..	..	..	..	..	..
53	6·6	2·8	238	WSW	ESE	34	6·2	1·1	265	WSW	E	14	7·2	4·1	231	..	..	3	8·5	4·3	249	..	..
169	7·2	4·0	319	NNW	Var.	111	7·4	4·4	325	NW	Var.	56	8·3	0·5	118	E	Var.	20	5·7	2·2	140	E	Var.
43	7·6	0·9	251	Var.		26	6·1	1·4	135	SE	NW	0	4·8	2·9	176	..	..	1	6·5	6·5	180	..	..
47	6·4	2·3	210	S	Var.	31	5·8	2·3	213	..	..	9	6·5	3·7	185	..	..	..	..	..	..	..	..
100	6·6	1·4	236	SW	Var.	57	5·5	0·9	192	S	Var.	31	5·8	10·8	129	SE	Var.	11	6·2	4·9	105	E	SE
91	6·0	3·8	240	SE—SW—NW		69	5·8	3·4	257	SE—SW—NW		37	4·8	2·6	221	SE—W		6	5·6	2·1	130	..	..
40	7·5	6·1	238	WSW	Var.	21	6·0	4·0	240	..	..	3	2·7	2·1	241	..	..	..	..	..	..	..	..
134	6·9	4·5	336	NNW	Var.	93	6·8	3·2	343	W—N—E		34	6·8	3·4	287	W	E	9	6·8	1·7	309	..	..
40	7·5	4·5	301	NW	Var.	33	7·4	5·3	290	S—NW		16	7·3	5·1	266	S—W—N		6	6·8	4·0	240	..	..
89	7·2	4·3	324	NNW	Var.	65	7·5	4·2	330	SW—NW—NE		28	6·2	0·6	313	NNW	SE	4	8·1	3·7	29	..	..
148	5·1	1·1	63	Var.		118	5·3	1·2	99	Var.		68	5·8	1·9	44	NE	Var.	35	4·3	2·0	76	NE—SE	
111	5·5	2·1	297	Var.		89	5·4	0·9	265	W	Var.	46	4·8	0·5	153	Var.		16	4·5	2·6	69	NE	
91	5·5	3·2	318	W—NE		52	5·6	1·8	8	N	Var.	20	6·1	1·7	45	E	Var.	4	4·7	3·5	80	..	..
30	6·5	2·8	300	WNW	SE	15	5·9	1·2	68	..	..	7	3·3	1·1	220	..	..	3	2·8	2·4	343	..	..
143	6·2	2·4	297	W	Var.	103	5·9	0·4	88	E	Var.	56	5·4	0·5	225	W	Var.	21	5·7	3·9	103	NE—S	
229	7·1	5·4	276	W	Var.	176	6·8	3·5	277	W	Var.	81	5·4	1·4	271	..	..	33	6·0	2·9	81	..	..
69	6·9	5·1	241	WSW	Var.	40	6·1	3·9	234	SE—SW—NW		20	5·9	1·8	168	SSW	N	8	6·0	4·3	78	..	..
47	11·0	9·1	299	SW—NW—NE		21	8·1	5·5	300	WNW	NE	7	7·7	5·8	331	..	..	1	0·5	0·5	10	..	..

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	62	6·0	3·2	225	WSW	ENE	61	6·8	4·2	238	WSW	Var.	56	5·0	3·2	255	WSW	Var.
Bahrein	201	12·5	8·8	332	N	NW	161	11·9	11·1	344	N	NW	106	10·2	8·7	337	NW—E	
Muscat	207	3·6	1·6	292	WNW	Var.	213	4·8	3·2	296	WNW	Var.	199	6·1	4·0	327	NW	Var.
Gwador	212	3·6	1·5	173	E—S—W		135	4·1	0·8	276	W	Var.	91	5·6	2·8	343	W—N—E	
Karachi*	273	10·5	9·5	265	W	SW	208	9·1	7·4	271	W	Var.	110	6·5	3·1	353	NW	Var.
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	334	3·3	2·0	184	S	Var.
Peshawar*	247	3·4	2·3	358	..	..	245	2·8	0·8	349	NNW	Var.	240	3·5	1·3	264	WNW	Var.
Lahore*	411	6·0	2·8	152	SSE	Var.	407	5·2	1·9	201	Var.		364	4·6	1·3	297	WNW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	60	6·9	1·2	216	W	Var.	56	7·7	1·7	254	WNW	Var.	44	6·7	1·2	352	NW	Var.
Ahmedabad	198	9·8	8·6	251	S—NW		157	9·9	9·3	257	SW—NW		77	7·7	5·6	236	SW	Var.
Ajmer	..	..	..	..	..	..	196	8·5	6·1	263	W	Var.	139	5·2	0·8	354	Var.	
Agra*	527	7·2	1·9	254	W	Var.	486	7·3	2·1	295	WNW	ESE	425	6·5	2·3	356	NNW	Var.
Allahabad	150	8·5	1·1	270	W	ESE	130	7·9	2·3	298	WNW	ESE	92	7·9	1·6	355	NW	E/SE
Patna	188	7·9	3·2	110	E/SE	W	165	7·7	2·9	107	E/SE	W	128	7·5	3·4	96	E	Var.
Rangpur	24	8·4	7·9	115	SE	E	20	9·0	8·3	112	NE—S		13	9·6	9·1	95	E	SE
Tezpur	120	4·9	9·5	152	E—S—W		102	5·1	1·4	179	E	Var.	81	5·3	1·6	158	E	SW
Calcutta*	334	8·2	4·8	213	SW	Var.	275	7·8	4·5	222	SW	Var.	167	6·3	3·2	216	SW	Var.
Dacca	150	7·8	5·6	163	E—S—W		93	7·9	4·8	164	SE	Var.	56	7·2	4·2	140	ESE	Var.
Chittagong	143	9·4	8·7	164	SE—SW		116	9·0	7·7	171	SE—SW		79	8·1	6·1	164	S	Var.
Akyab*	209	7·4	6·0	190	E—S—W		152	7·5	6·2	211	E—S—W		87	6·8	4·8	217	SW	Var.
Mandalay	180	11·2	11·1	179	S		174	12·1	11·9	186	S	SW	134	8·0	6·7	212	SW/S	Var.
Rangoon	177	9·3	7·7	230	SE—W		147	9·5	8·5	244	SE—W		98	8·9	7·9	247	SE—SW—NW	
Jubbulpore	..	..	..	..	..	..	144	9·5	8·1	276	W	Var.	91	7·1	4·7	294	WNW	Var.
Ranchi	..	..	..	..	..	..	23	7·5	4·4	301	WNW	Var.	16	5·8	2·4	326	WNW	NE
Sambalpur	126	7·0	5·5	247	WSW	Var.	108	9·5	7·4	272	SW—NW—NE		60	9·3	6·7	292	WNW	ENE
Poona*	..	..	..	..	..	..	248	11·7	10·6	259	W	SW	58	12·4	11·6	264	W	SW
Hyderabad	..	..	..	..	..	..	145	14·7	14·0	279	W	NW	103	12·8	12·2	286	W	NW
Waltair	171	10·2	9·1	256	W	SW	158	11·0	10·2	271	SW—NW		113	12·9	10·6	292	SW—N	
Mangalore	185	9·5	8·7	270	W	Var.	131	11·9	11·4	280	W	NW	40	10·1	7·5	291	W—N	
Bangalore*	..	..	..	..	..	..	309	8·6	6·6	259	..	..	168	9·6	9·4	277	SW—NW	
Madras	278	11·7	11·1	268	SW—NW		278	12·4	11·8	282	SW—NW		272	10·9	10·1	285	SW—NW	
Port Blair	267	11·8	11·0	236	S—W		209	11·9	11·4	241	SE—W		106	8·2	7·1	241	SE—W	
Trivandrum	167	8·1	7·6	307	NW	W	166	11·3	10·6	304	NW	W	103	13·8	12·9	303	NW	W

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used;

8 km. above Sea Level over India—July.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
49	4·9	3·5	310	W—N		39	6·4	4·6	31	N—E		27	15·0	14·1	41	N—E		4	8·9	8·5	44	..	..
66	7·7	4·2	325	NW	Var.	47	7·1	1·0	67	NW—NE—SE		19	6·9	3·1	36	NW—NE—SE		6	6·3	5·5	54	..	..
168	6·4	4·0	17	N	Var.	128	7·8	5·6	49	NE	Var.	52	8·6	7·2	72	N—SE		6	7·2	7·1	76	..	..
68	6·2	4·4	353	W—N—E		42	7·6	6·1	17	N	NW	11	7·0	4·0	56	N—E		1	5·5	5·5	45	..	..
79	8·4	6·4	32	NW—E		56	11·3	9·6	49	N—E		21	12·3	11·2	59	N—SE		5	13·1	11·8	53	..	..
323	5·8	4·3	294	8W—N		277	6·9	4·6	304	W—N		143	7·2	1·5	347	Var.		76	9·0	4·3	334	NW	Var.
232	5·2	4·2	302	WNW	Var.	215	6·0	4·7	320	W—N		172	7·9	4·9	324	WNW	Var.	78	11·7	8·0	295	SW—N	
303	5·3	2·9	337	NNW	Var.	251	6·3	4·1	344	N	NW	160	6·4	2·4	290	Var.		114	9·2	5·3	267	SW	Var.
288	5·2	3·1	319	NW	SE	210	5·0	2·1	317	NW	SE	119	6·1	2·1	241	SW	Var.	81	9·8	6·4	247	SW	Var.
27	6·5	2·0	35	Var.		16	5·8	1·7	10	W	ESE	9	8·1	2·8	112	..	..	3	8·2	7·7	234	..	..
38	6·5	1·6	221	Var.		27	4·5	2·0	77	NE—SE		11	4·6	2·6	77	..	..	4	6·4	5·0	96	..	..
107	6·1	2·8	53	E	Var.	72	6·3	3·4	42	N—E		36	7·4	1·9	59	NE	Var.	7	9·1	3·8	76	..	..
329	6·7	2·5	343	N	Var.	257	6·1	1·7	27	NNW	E/SE	172	6·0	2·0	120	ESE	Var.	115	6·4	3·2	113	E	SE
47	7·1	2·3	56	Var.		28	6·9	1·9	30	NNW	ESE	10	8·0	6·2	88	..	..	3	7·5	5·6	74	..	..
96	7·6	4·0	100	E	Var.	73	6·9	3·6	108	E	W	38	7·9	6·1	94	E	SE	16	7·9	7·4	98	..	..
11	10·3	9·8	95	E	SE	7	7·9	7·1	105	..	..	4	7·4	4·2	124	..	..	..	..	..	..	..	..
54	5·3	2·8	114	E/SE	SW/W	44	5·2	2·7	129	E/SE	WSW	14	4·9	3·6	110	E	SW	12	4·6	3·3	90	E	
114	5·8	2·1	193	8W	Var.	79	5·3	2·0	162	E—S—W		44	5·3	2·9	112	SE	Var.	15	7·7	6·9	111	E	SE
22	7·0	4·1	106	E	W/SW	10	8·9	7·4	95	..	..	2	9·5	7·1	84	..	..	1	5·0	5·0	210	..	..
45	7·5	5·5	152	E—SW		24	6·9	5·3	138	E	SE	6	5·8	4·3	140	..	..	..	..	..	..	..	..
59	6·2	3·2	223	SW	Var.	39	5·4	1·4	195	E—S—W		18	5·5	4·4	117	NE—S		5	8·0	7·3	99	..	..
69	6·7	2·2	253	SE—SW—NW		36	5·2	2·7	221	W	SE	12	4·7	2·3	175	S		..	..	..	..	..	..
54	8·7	7·2	252	SE—SW—NW		20	7·3	4·5	255	W	SW	7	6·4	1·9	147	..	..	..	..	..	..	..	..
53	5·5	1·6	314	Var.		26	5·5	3·3	18	..	..	12	6·6	1·6	69	..	..	1	10·5	10·5	85	..	..
9	4·0	1·2	7	WNW	NE	5	4·3	2·9	45	..	..	4	6·1	5·7	70	..	..	..	..	..	..	..	..
36	7·2	3·1	290	NW	Var.	23	5·3	0·9	303	..	..	8	5·0	1·5	132	..	..	2	6·3	6·1	84	..	..
15	6·1	3·5	248	E—S—W		9	3·4	1·9	244	..	..	4	4·1	2·8	161	..	..	3	4·8	4·7	104	..	..
65	8·4	7·7	278	SW—NW		39	7·7	6·9	283	W	NW	16	5·3	2·4	293	..	..	4	4·7	3·1	87	..	..
56	10·1	9·3	287	SW—N		25	8·5	5·8	289	SW—NW		3	8·7	7·7	68	..	..	1	9·0	9·0	100	..	..
16	8·2	5·9	274	W/NW	E	5	5·5	3·7	165	..	..	3	7·8	7·5	122	..	..	..	..	..	..	..	..
183	6·1	5·8	277	S—NW		50	4·5	2·5	263	W	NW	25	4·5	2·1	124	ESE	SW	11	7·5	7·0	97	E	SE
206	9·2	8·4	276	SW—NW		141	8·4	7·2	270	SW—NW		68	6·2	1·7	256	WSW	E	21	6·0	3·0	85	NW—NE—SE	
58	6·3	4·0	233	8E—SW—NW		45	6·0	3·1	222	S—NW		24	5·5	2·8	138	NE—S		7	7·0	7·0	106	..	..
45	12·7	11·0	303	NW	W	18	13·0	10·7	306	W—NE		3	13·7	10·8	315	..	..	1	10·0	10·0	95	..	..

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	62	7·5	5·7	241	WSW	NE	62	7·5	6·0	246	W	SW	56	6·8	5·5	263	SW—NW	
Bahrein	206	8·8	6·4	346	NNW	Var.	178	7·7	6·3	351	NNW	Var.	149	6·8	5·2	348	NW—E	
Muscat	205	2·6	0·5	299	Var.		209	3·7	2·1	303	WNW	Var.	206	5·4	3·1	347	W—N—E	
Gwador	185	3·1	1·6	157	E—S—W		77	4·0	0·7	344	Var.		38	5·4	3·2	357	NW	Var.
Karachi*	275	9·4	9·0	269	SW—NW		183	8·3	7·0	275	SW—NW—NE		96	6·8	3·9	13	N	Var.
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	335	2·9	1·1	209	S	Var.
Peshawar*	244	3·3	2·2	350	..	..	244	2·7	0·8	360	NNW	Var.	235	3·1	1·4	255	NW	Var.
Lahore*	406	5·5	2·5	198	Var.		400	4·6	1·9	227	W	Var.	369	3·8	1·4	301	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	61	8·1	2·3	233	SE/E	W	58	7·7	0·8	240	SE	WNW	51	5·3	1·9	63	NW—NE—SE	
Ahmedabad	197	9·3	8·6	261	SW—N		160	9·2	8·5	258	SW—N		67	7·4	5·5	235	SW	Var.
Ajmer	..	..	..	..	..	..	179	8·0	5·6	267	W	Var.	114	4·6	1·1	78	ENE	Var.
Agra*	506	7·3	2·3	276	W	Var.	491	7·1	2·1	313	WNW	ESE	423	6·0	1·7	41	NW	Var.
Allahabad	137	7·4	1·6	259	W	Var.	117	6·8	1·5	282	W	ESE	78	6·2	1·1	328	WNW	Var.
Patna	192	7·6	1·9	113	ESE	Var.	172	7·5	1·9	95	ESE	Var.	141	7·3	2·8	97	E	Var.
Rangpur	29	5·9	4·9	130	NE—SE—SW		22	6·0	5·1	117	NE—S		13	6·5	5·4	101	NE—S	
Tezpur	118	5·1	1·8	223	WSW	ESE	103	5·6	2·0	226	WSW	E	73	5·8	1·7	216	WSW	E
Calcutta*	343	6·8	2·9	200	SW	Var.	302	6·4	2·3	196	SW	Var.	204	5·7	2·1	186	SSW	Var.
Dacca	165	7·1	5·2	161	E—S—W		117	7·0	4·5	161	SE	Var.	71	6·8	3·6	130	SE	Var.
Chittagong	157	8·8	8·2	167	E—SW		131	8·3	7·4	174	SE—SW		86	7·2	5·4	165	E—SW	
Akyab*	224	6·8	5·5	185	SE—W		176	6·9	5·1	198	SE—W		112	6·6	4·3	194	SE—W	
Mandalay	181	10·5	10·4	181	S		178	10·3	10·0	187	S	SW	134	6·2	4·9	211	SW	Var.
Rangoon	200	8·6	7·5	237	S—NW		181	8·4	6·4	251	WSW	Var.	131	7·9	6·9	254	S—NW	
Jubbulpore	..	..	..	..	..	..	157	8·8	6·5	280	W	Var.	101	6·6	4·3	288	WNW	Var.
Ranchi	..	..	..	..	..	..	22	7·7	3·2	330	NW	SE	15	6·4	1·0	81	..	..
Sambalpur	134	6·7	5·1	242	WSW	Var.	114	8·5	6·1	271	W	Var.	71	7·4	3·5	286	W	Var.
Poona*	..	..	..	..	..	..	263	10·4	10·2	260	SW—NW		70	12·2	11·8	266	W	Var.
Hyderabad	..	..	..	..	..	..	139	12·3	10·3	277	WNW	Var.	98	9·1	7·7	285	WNW	Var.
Waltair	175	9·1	8·5	252	W	SW	155	8·6	7·7	267	SW—NW		108	8·6	7·4	292	WNW	Var.
Mangalore	198	8·5	7·4	285	W	Var.	146	9·5	8·5	292	W—N		59	7·4	5·9	296	WNW	Var.
Bangalore*	..	..	..	..	..	..	329	7·8	7·5	268	..	..	167	8·7	8·2	285	WNW	ENE
Madras	279	10·6	9·7	268	S—NW		276	10·8	9·9	285	S—NW		262	9·0	8·0	288	W	NW
Port Blair	260	11·0	10·6	237	SE—W		216	11·1	10·4	240	SE—W		123	7·9	6·1	238	SE—W	
Trivandrum	152	7·1	6·4	313	W—N		145	9·2	8·6	311	W—N		81	11·1	10·2	315	W—NE	

* For stations marked with an asterisk the available data up to the end of 1931 only have been used;

8 km. above Sea Level over India—August.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D′	n	V	v	D	D″	D″
44	4·7	2·2	314	W—N—E		41	6·9	4·9	41	NE	W	29	10·1	9·3	54	NE	E	6	6·6	3·6	97	..	..
118	7·3	3·7	3	NW	Var.	82	6·9	2·6	44	Var.		57	6·8	2·3	49	Var.		27	6·2	2·6	38	W—N—E	
199	5·7	3·9	21	NNE	Var.	168	6·8	4·8	44	Var.		90	7·5	3·8	52	Var.		14	6·3	5·4	75	NE—SE	
30	6·3	4·0	7	W—N—E		17	7·8	5·4	8	W—NE		2	4·7	4·7	125	..	..	1	5·0	5·0	250	..	..
71	8·4	6·6	30	NNE	Var.	47	10·4	8·8	36	N—E		26	9·5	7·8	51	NW—E		3	3·5	3·4	4	..	..
332	6·1	5·2	300	SW	N	272	6·6	4·2	300	WNW	Var.	156	6·4	1·1	244	S	Var.	92	7·4	3·2	265	WSW	Var.
223	4·9	3·0	303	NW	Var.	207	6·1	5·2	313	W—N		172	7·5	4·5	292	SW—NW—NE		84	12·6	9·0	268	SW—NW—NE	
324	4·5	2·3	331	NNW	Var.	277	5·7	3·7	337	W—NE		199	6·0	3·1	258	WSW	Var.	129	8·5	6·4	258	W	SW
233	4·2	1·5	357	NW	Var.	187	8·7	0·2	351	SE	NW	119	6·0	3·4	224	SW	Var.	87	8·8	7·0	239	WSW	Var.
33	5·2	2·1	87	SE	Var.	20	5·1	1·9	37	NW—NE		4	4·3	3·0	123	..	..	.	..	..	..	..	..
30	5·2	1·2	223	W	Var.	21	5·3	1·5	51	NE—S		12	4·5	3·1	72	NE	E	3	5·3	4·9	91	..	..
85	5·4	2·5	69	E	Var.	66	5·1	2·3	47	Var.		38	7·1	3·8	48	ENE	Var.	15	6·8	5·4	86	NE—S	
323	5·9	1·9	53	E	Var.	266	5·4	1·5	51	E/SE	WNW	180	5·5	2·0	89	E	Var.	126	6·0	3·4	93	NE—SE	
50	5·2	0·5	348	Var.		27	5·7	0·1	270	..	..	13	6·1	1·0	42	..	..	3	4·5	4·5	105	..	..
110	6·8	2·4	116	E	Var.	87	6·5	3·3	107	E/SE	WNW	56	5·2	3·3	120	E—SW		22	6·8	4·7	98	NE—SE	
9	8·5	7·6	100	NE—S		8	7·4	6·5	99	..	..	3	3·3	2·6	107	..	..	..	..	..	..	..	..
47	5·7	1·4	168	E	WSW	35	5·1	1·8	169	SW/W	E	14	3·8	1·8	131	..	..	4	3·8	1·6	153	..	..
148	5·7	2·6	152	SE	Var.	105	5·5	2·6	144	SE	Var.	54	5·6	4·2	120	NE—S		16	7·1	4·6	113	E	SE
38	6·1	2·2	128	E	Var.	25	7·1	4·1	112	SE	Var.	6	6·3	5·6	124	..	..	2	6·7	6·7	115	..	..
54	5·9	3·6	162	SE	Var.	33	5·6	4·3	136	SE	E	13	6·2	4·6	123	..	..	1	9·0	9·0	80	..	..
81	5·7	3·6	172	SE—W		57	6·0	4·2	141	SE	Var.	28	6·5	5·4	116	E—S		11	8·1	7·3	98	NE—SE	
84	4·9	2·5	236	Var.		51	3·9	1·3	178	ESE	SW	31	5·1	2·9	93	E	SW	4	3·8	3·5	59	..	..
81	6·8	5·0	255	WSW	Var.	50	5·3	2·8	247	W	SW	19	4·7	1·5	129	..	..	2	8·7	8·5	93	..	..
62	5·7	2·7	274	W	NE	46	5·0	1·4	252	WSW	Var.	24	5·2	1·1	113	W	E	5	8·0	7·2	93	..	..
5	5·6	3·0	281	..	..	4	5·0	3·0	208	..	..	..	..	..	..	..	..	..	..	..	..	..	..
43	5·8	2·5	278	W	Var.	25	4·9	2·0	252	..	..	10	5·2	4·5	106	..	..	4	8·5	8·1	98	..	..
16	6·3	5·0	270	NW	Var.	11	3·7	1·3	358	N	NE	5	5·2	5·0	42	..	..	3	9·0	8·9	88	..	..
68	6·1	4·6	280	WNW	Var.	48	5·8	2·9	278	S—NW		31	6·0	1·8	97	W	NW	15	6·9	5·1	94	ENE	
61	7·9	6·5	288	WNW	Var.	41	6·5	3·9	296	WNW	SSE	14	5·7	1·7	89	..	..	2	6·5	6·5	99	..	..
30	5·6	2·3	310	NW	Var.	17	4·0	1·1	86	..	.	8	5·0	4·1	117	..	..	2	6·5	4·7	137	..	..
101	6·6	5·5	290	W	Var.	61	5·3	3·7	281	W	NW	27	4·6	0·6	352	SW—N		12	5·7	4·3	85	..	..
213	8·3	6·7	280	W	NW	149	7·5	4·7	272	W	NW	64	5·7	1·5	126	SW	Var.	19	7·6	3·9	87	E	Var.
67	6·8	4·1	239	Var.		43	5·4	1·6	199	E—S—W		19	5·6	2·1	140	S	Var.	6	7·1	7·0	90	..	..
51	10·8	8·6	323	W—N—E		14	10·1	8·0	336	..	..	3	8·5	8·5	99	..	..	3	5·2	4·8	84	..	..

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	55	3·3	1·2	113	N—E—S		52	3·8	1·2	144	ESE	Var.	50	3·6	1·7	195	S—W	
Bahrein	205	6·2	4·3	345	N	Var.	196	6·9	5·4	353	N	Var.	178	7·2	5·1	354	N	Var.
Muscat	206	3·4	2·0	290	W	Var.	211	4·5	3·2	327	NNW	Var.	208	5·8	4·4	14	NW—E	
Gwador	165	3·5	1·4	253	WSW	Var.	104	4·3	1·9	345	Var.		78	5·3	2·5	22	NW—E	
Karachi*	294	8·6	7·4	276	W—NE		214	6·9	4·9	284	SW—NW—NE		166	5·5	2·8	17	Var.	
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	328	2·5	0·7	267	S	Var.
Peshawar*	253	2·8	1·6	336	NW—NE		253	2·7	1·7	350	W—NE		250	3·4	1·7	288	NW	Var.
Lahore*	394	4·9	1·7	237	W	Var.	393	4·0	1·8	273	WNW	Var.	289	3·8	1·9	317	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	58	6·8	2·7	283	WNW	Var.	56	6·3	2·7	310	NW	Var.	50	6·8	5·1	331	NNW	Var.
Ahmedabad	204	7·5	5·9	292	SW—N		195	5·7	3·2	285	W	Var.	154	5·3	1·7	86	E	Var.
Ajmer	..	..	..	..	..	..	198	7·0	4·9	287	WNW	Var.	185	4·8	2·6	25	NNE	Var.
Agra*	515	6·6	2·8	300	NW	Var.	500	6·2	3·1	325	NW	Var.	485	5·9	3·5	347	NNW	Var.
Allahabad	141	6·8	0·5	120	Var.		126	6·6	0·2	9	Var.		112	7·2	1·6	31	Var.	
Patna	198	5·6	1·6	130	ESE	Var.	190	5·4	1·0	138	ESE	Var.	176	5·5	0·6	88	Var.	
Rangpur	22	3·3	1·2	180	SE	Var.	21	3·0	0·8	73	E	Var.	19	2·4	0·5	85	SE	Var.
Tezpur	126	4·1	0·7	151	E	WSW	111	5·0	0·7	220	ENE	WSW	80	4·5	1·3	192	E	WSW
Calcutta*	329	5·9	3·1	183	SW	Var.	306	5·8	2·6	175	S	Var.	254	5·1	1·7	153	S	Var.
Dacca	181	5·1	3·4	175	S	Var.	142	4·8	2·9	164	S	Var.	114	4·9	2·6	139	S	Var.
Chittagong	156	6·0	4·4	157	S	Var.	146	5·8	4·2	164	S	Var.	131	5·7	3·9	155	SSE	Var.
Akyab*	310	4·6	2·2	164	SE	Var.	285	5·3	2·3	188	S	Var.	240	5·3	2·6	195	SSE	Var.
Mandalay	178	6·9	6·1	181	S		166	6·9	5·8	182	S	Var.	139	5·2	3·2	171	S	Var.
Rangoon	203	6·1	3·8	237	WSW	Var.	177	5·9	3·6	242	SW	Var.	136	5·3	2·5	230	SW	Var.
Jubbulpore	..	..	..	..	..	..	183	6·8	1·9	297	NW	Var.	159	6·3	3·5	22	N	Var.
Ranchi	..	..	..	..	..	..	30	4·8	1·8	348	NW	Var.	8	4·7	3·0	23	NW—E	
Sambalpur	135	5·2	1·1	222	Var.		127	6·4	1·4	259	Var.		101	6·9	1·2	18	Var.	
Poona*	..	..	..	..	..	..	299	5·9	3·9	277	WNW	Var.	222	5·6	0·6	269	Var.	
Hyderabad	..	..	..	..	..	..	165	9·4	6·9	295	NW/W	Var.	132	7·5	4·6	298	WNW	Var.
Waltair	179	6·0	4·2	251	WSW	NE	175	6·0	3·6	268	W	Var.	132	6·1	3·1	302	Var.	
Mangalore	199	6·1	4·6	290	S—W—N		176	7·7	6·5	292	S—W—N		107	7·1	4·5	290	WNW	Var.
Bangalore*	..	..	..	..	..	..	349	5·5	4·6	276	..	..	254	6·3	4·9	292	WNW	Var.
Madras	269	9·0	7·5	269	S—NW		269	8·1	6·6	285	WNW	Var.	262	6·4	4·7	290	WNW	Var.
Port Blair	241	8·7	7·8	248	WSW	Var.	200	8·3	7·0	246	WSW	Var.	135	5·8	3·9	242	WSW	Var.
Trivandrum	163	6·8	6·1	315	W—N		158	8·7	7·9	313	W—N		115	10·0	8·8	318	W—NE	

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—September.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
48	5·1	2·6	58	E	Var.	43	9·2	8·2	39	NE	E	27	11·5	10·3	43	N—E		6	7·3	6·5	73	..	..
139	6·7	3·6	11	N	Var.	104	7·1	2·4	32	NW—NE—SE		73	6·5	3·0	56	NW—NE—SE		28	6·1	0·9	10	NW—E	
200	7·1	5·6	46	NW—E		176	8·3	6·6	54	NW—E		92	6·3	3·9	46	NW—E		21	6·6	2·5	315	WNW	ENE
65	6·3	4·8	29	NW—E		47	7·8	6·7	37	NW—NE		17	7·5	4·5	328	NW—E		2	8·7	5·7	294	..	..
148	7·5	5·7	41	W—N—E		123	8·9	7·4	46	NW—E		82	7·4	2·3	12	NE	Var.	29	9·4	3·4	272	SW	Var.
328	5·1	3·0	313	NW	Var.	306	6·2	3·4	290	SW—N		213	7·2	2·3	297	W	Var.	122	12·4	10·1	285	S—W—N	
249	5·0	4·0	294	SW—N		242	5·7	4·7	301	NW	W	217	7·4	5·6	289	SW—N		123	14·9	13·1	278	SW—N	
380	5·0	3·5	323	NNW	Var.	365	6·1	4·6	324	W—N		313	8·5	6·2	268	SW—N		207	15·2	13·7	255	SW—NW	
322	4·1	1·3	323	NW	Var.	285	4·1	0·2	280	SE	NW	239	7·5	5·1	244	S—NW		187	15·2	13·7	255	SW—N	
35	5·0	2·9	353	NNW	Var.	28	4·8	0·7	255	SSW	NNW	11	6·3	5·0	250	S—W		2	8·7	8·7	249	..	..
135	6·2	3·6	75	E	Var.	111	5·6	3·3	66	NW—E		72	5·6	2·7	65	NE	E	25	6·0	1·4	54	W	ENE
164	5·7	3·4	35	NE	Var.	137	5·8	2·3	35	NNE	Var.	95	6·9	1·3	297	Var.		43	7·9	3·0	301	Var.	
436	5·8	3·3	344	NNW	Var.	396	5·4	2·2	311	SW—N		330	6·5	3·3	260	WSW	Var.	260	8·8	5·4	254	WSW	Var.
76	7·2	0·8	106	Var.		43	7·2	0·2	6	SW	ENE	23	6·7	2·2	112	E	SW	13	10·9	3·8	105	..	..
155	5·0	0·4	190	Var.		125	4·6	1·4	210	W	Var.	91	5·0	2·3	227	SW	W	38	6·0	1·9	211	SW	Var.
16	3·8	1·4	159	E	WSW	14	3·7	1·6	200	SW	W	12	6·3	4·4	238	WSW	E	..	..	..	..	..	..
56	4·8	1·5	189	SW	Var.	41	4·6	2·1	221	W	SW	19	4·4	0·2	73	..	..	4	4·6	3·6	160	..	..
200	4·9	2·0	158	S	Var.	158	5·2	2·1	168	E—S—W		87	5·5	2·4	133	E—S—W		41	5·7	2·5	125	ESE	Var.
81	4·8	2·6	146	S	Var.	52	5·1	2·8	135	E—S—W		22	4·9	1·5	110	..	..	2	5·5	5·0	36	..	..
97	5·3	3·7	151	SE	Var.	70	5·1	3·4	148	E—S—W		38	4·6	2·4	123	E—SW		7	3·6	0·7	159	..	..
180	4·9	3·0	141	E—SW		137	4·6	3·0	123	E—S		86	5·4	3·6	105	NE—S		45	6·7	4·7	96	E—S	
95	4·9	2·4	167	Var.		71	4·4	1·9	167	SE	Var.	32	4·1	1·7	109	Var.		8	4·9	2·4	86	..	..
82	5·0	0·9	165	SE	Var.	43	4·6	1·8	80	N—E—S		13	5·9	4·7	80	..	..	1	7·0	7·0	95	..	..
131	6·4	3·1	39	Var.		95	6·2	1·4	80	W—N—E		59	5·9	2·3	138	WSW	E	22	6·0	1·2	110	E	W
26	3·4	0·2	357	N	Var.	23	4·4	1·8	21	SW/W	E	16	6·5	3·5	37	SE—W		7	7·9	3·8	207	WSW	SE
70	6·4	0·9	29	Var.		46	6·4	1·3	107	E	Var.	17	6·0	4·8	87	..	..	7	7·1	6·7	100	..	..
156	4·6	0·7	102	Var.		112	4·2	0·7	112	E	Var.	68	4·4	1·8	76	NE	Var.	41	5·9	4·3	95	NE—SE	
104	6·1	2·8	322	NW	Var.	78	6·1	1·6	333	N	Var.	39	5·5	2·7	96	E	SE	19	6·5	5·0	94	ESE	NW
87	5·0	1·1	348	NW	Var.	58	4·6	1·7	51	E	Var.	28	5·5	4·0	90	N—E—S		10	7·6	6·7	94	..	..
55	6·2	0·5	303	Var.		36	8·9	3·8	283	ESE	W	9	3·5	0·9	93	..	..	1	3·5	3·5	50	..	..
172	5·4	1·6	298	NW	Var.	116	5·2	1·6	278	Var.		61	5·2	1·1	111	Var.		26	6·2	4·8	94	E	
226	6·4	4·1	284	W	Var.	182	6·2	2·8	279	W	Var.	115	5·7	1·1	99	E	Var.	39	7·0	5·6	92	NE—S	
94	5·3	2·0	224	W	Var.	74	5·2	1·2	170	W	ESE	43	5·4	2·9	93	NE—S		15	7·8	7·2	88	NE—SE	
76	9·7	6·8	330	W—N—E		37	8·6	5·1	353	W—N—E		11	5·6	3·0	10	..	..	5	7·8	4·5	92	..	..

for the remaining stations, data up to the end of 1934 have been used.

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APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	70	5·4	4·2	80	NE	E	65	6·0	4·5	75	E	NE	59	6·3	5·0	71	N—E	
Bahrein	214	6·3	4·8	349	N	Var.	212	8·4	5·1	350	N	Var.	189	7·6	4·7	346	N	Var.
Muscat	245	3·6	2·5	287	WNW	Var.	247	4·2	2·1	311	WNW	Var.	240	4·5	2·5	34	NE	Var.
Gwador	210	4·5	1·6	346	Var.		175	5·0	2·7	10	NNE	Var.	157	4·6	2·5	6	NNE	Var.
Karachi*	310	6·7	4·3	302	WNW	Var.	301	5·0	3·1	295	W	Var.	285	5·0	2·0	342	Var.	
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	336	2·6	1·1	286	NW	S
Peshawar*	267	2·3	1·1	317	..	..	272	3·0	2·2	345	W—NE		269	3·7	2·2	314	NNW	Var.
Lahore*	402	4·6	0·7	315	W	Var.	401	3·9	1·6	308	NW	Var.	402	4·5	2·7	306	NW	Var.
Simla*	..	..	..	..	.	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	62	5·1	0·7	140	SE	Var.	62	4·8	0·3	80	Var.		58	6·3	2·5	321	NW	E
Ahmedabad	211	5·5	2·4	35	Var.		210	4·4	1·8	58	Var.		202	4·9	2·0	64	ENE	Var.
Ajmer	..	..	..	..	..	..	214	5·6	2·0	278	W	Var.	207	4·8	2·0	311	NW	Var.
Agra*	544	5·5	1·7	300	Var.		545	5·2	2·5	317	NW	Var.	539	6·8	4·6	321	NW	Var.
Allahabad	146	4·7	1·2	305	WNW	Var.	143	4·8	2·3	321	NW	Var.	138	6·7	4·6	316	NW	Var.
Patna	204	4·5	3·4	281	Var.		199	4·9	1·4	310	WNW	Var.	190	6·4	2·8	306	WNW	Var.
Rangpur	22	2·6	1·2	76	N	SE	19	2·2	0·3	237	SE	Var.	18	3·0	1·8	294	NW	Var.
Tezpur	130	4·5	2·3	91	E	Var.	120	4·1	1·3	109	E	Var.	96	4·3	1·8	281	WSW	E
Calcutta*	337	4·8	0·5	14	N	Var.	331	4·7	1·0	13	N	Var.	311	5·1	1·2	316	Var.	
Dacca	203	4·0	0·4	238	Var.		195	3·9	0·8	240	Var.		171	4·7	2·0	249	Var.	
Chittagong	169	4·2	1·3	65	NNE	SSE	166	3·8	0·5	130	N	Var.	157	4·3	1·7	200	SSW	Var.
Akyab*	343	3·9	1·1	98	SE	Var.	333	3·9	1·3	147	SSE	Var.	307	4·3	1·6	160	SE	Var.
Mandalay	181	4·1	3·4	172	N—E—S		178	4·1	2·6	175	S	Var.	168	3·8	2·0	180	Var.	
Rangoon	211	5·2	2·9	100	ESE	Var.	207	5·6	4·0	111	ESE	Var.	191	5·9	4·4	115	ESE	Var.
Jubbulpore	..	..	..	..	..	..	205	4·8	2·1	36	Var.		198	6·1	4·0	10	N	Var.
Ranchi	..	..	..	..	..	..	30	4·8	1·5	327	NW	Var.	27	5·5	2·7	340	Var.	
Sambalpur	148	4·1	1·8	62	ENE	Var.	146	4·9	2·2	56	Var.		138	4·7	1·7	22	Var.	
Poona*	..	..	..	..	..	..	326	5·3	1·7	72	Var.		298	5·7	3·4	77	ENE	Var.
Hyderabad	..	..	..	..	..	..	128	6·6	2·7	65	E	Var.	158	6·2	3·7	42	ENE	Var.
Waltair	208	5·6	2·4	51	NE	Var.	200	5·7	3·1	56	ENE	Var.	177	5·4	2·7	60	ENE	Var.
Mangalore	206	4·6	0·2	257	Var.		195	5·1	0·5	71	E	Var.	161	6·5	2·5	82	E	Var.
Bangalore*	..	..	..	..	..	..	396	5·1	0·9	10	..	..	346	5·9	2·8	28	W—N—E	
Madras	273	5·8	0·8	311	Var.		266	5·5	1·4	15	NE	Var.	244	5·5	2·5	17	Var.	
Port Blair	267	6·1	1·6	216	WSW	Var.	232	6·1	1·4	200	Var.		178	5·0	1·0	159	Var.	
Trivandrum	153	5·0	3·7	307	NW	Var.	151	6·1	4·3	305	NW	Var.	121	7·4	4·7	308	NW	Var.

* For stations marked with an asterisk the available data up to the end of 1921 only have been used ;

8 km. above Sea Level over India—October.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
57	9·4	8·8	47	N—E		44	9·9	9·0	48	N—E		27	8·7	6·2	63	N—SE		10	9·4	8·3	57	E	NE
150	8·3	4·9	346	N	Var.	125	8·3	4·8	342	WNW	Var.	79	8·9	6·1	287	WNW	Var.	32	13·9	12·5	277	SW—NW	
241	6·3	4·0	55	NE	Var.	229	6·8	4·2	47	NW—E		160	8·5	4·1	298	NW	Var.	34	11·3	7·7	276	SW—NW	
125	6·5	4·3	10	N	Var.	114	7·3	4·8	4	W—NE		85	11·1	7·8	295	NW	Var.	9	17·1	14·6	264	..	..
270	6·7	3·9	23	NE	Var.	241	7·5	4·1	12	NE	Var.	182	10·3	6·4	292	W	Var.	86	15·7	13·8	277	SW—NW	
334	5·6	5·2	307	SW—N		314	8·3	6·2	304	SW—N		180	10·1	7·1	295	WNW	Var.	85	15·7	13·2	285	SW—N	
265	5·1	3·1	297	NW	Var.	258	5·5	3·8	302	W—N		244	8·9	6·9	288	SW—N		177	15·2	13·8	283	SW—N	
397	5·9	4·0	309	NW	Var.	388	6·8	4·8	311	SW—N		342	10·6	8·7	256	SW—N		255	18·4	16·5	276	SW—N	
414	4·9	2·1	314	NW/W	SE	394	5·6	1·7	300	NW	SE	357	10·2	8·4	271	S—NW		258	18·5	16·9	269	SW—NW	
47	6·1	2·9	311	NW	Var.	35	6·5	2·4	258	S—W—N		17	9·6	6·9	242	W	SW	..	..	..	..	..	..
186	5·9	1·4	40	Var.		156	5·8	1·5	302	W	Var.	111	8·6	5·3	278	W	Var.	22	11·0	8·9	262	SW—NW	
196	5·6	2·3	324	N	Var.	160	6·7	3·0	317	W—N—E		102	11·3	8·6	279	W	Var.	36	16·4	14·8	271	SW—NW	
524	7·4	5·4	311	NW	Var.	503	7·3	5·0	305	SW—N		462	11·8	10·0	277	SW—N		377	18·4	17·1	270	SW—NW	
119	6·8	4·6	303	NW	Var.	91	7·1	5·0	283	S—NW		49	10·7	9·1	265	W	SW	8	14·2	13·8	270	..	
175	6·5	3·8	292	WNW	Var.	153	7·2	5·0	273	SW—NW		117	11·3	9·4	267	W	Var.	34	17·3	16·4	260	S—NW	
17	3·3	2·6	251	S—NW		17	8·5	7·8	264	SW—NW		16	12·8	11·5	261	SW—NW		1	15·0	15·0	230	..	..
74	4·9	3·7	248	W	SW	58	7·6	6·8	253	W		30	14·7	14·2	264	W		5	14·0	13·4	276	..	
284	5·9	2·8	251	WSW	Var.	244	7·2	4·3	253	WSW	Var.	164	9·0	6·6	264	W	Var.	60	12·5	10·0	263	S—NW	
147	6·0	3·9	249	WSW	Var.	120	7·1	5·4	259	W		64	8·7	7·5	263	SW—NW		7	14·1	13·9	257	.	
122	4·6	2·3	215	Var.		93	5·1	2·9	249	W	SW	56	6·3	4·1	258	WSW	Var.	6	9·6	8·8	260	..	..
267	4·4	1·7	303	Var.		240	4·9	1·8	225	WSW	Var.	166	6·1	1·8	258	W	Var.	93	8·4	3·8	258	W	Var.
132	4·5	1·8	204	Var.		98	4·7	2·3	254	S—W		55	6·5	4·6	256	SE—SW—NW		8	9·5	4·3	275	..	..
133	4·9	3·7	101	NE—S		91	4·6	3·2	89	NE—SE		45	4·8	1·6	90	NE		11	5·3	2·4	76	..	..
180	5·9	3·1	350	NNW	Var.	155	5·9	2·6	281	W	Var.	116	7·3	5·2	262	SW—NW		18	12·3	11·6	251	W	SW
20	5·3	2·3	266	SE—SW—NW		17	6·3	4·7	249	S—NW		15	9·5	7·6	265	S—NW		2	5·3	5·1	248	..	..
124	4·6	1·0	326	Var.		104	4·7	2·0	265	SW	Var.	66	6·0	3·6	256	S—NW		21	8·1	6·1	235	SW—N	
276	5·0	2·0	65	Var.		234	4·4	1·6	32	NE	Var.	188	5·3	0·6	330	W	Var.	131	6·4	2·4	253	W	Var.
148	5·4	2·7	39	NE	Var.	135	5·0	2·4	77	Var.		115	4·6	2·4	89	Var.		70	5·1	2·3	109	Var.	
139	4·7	1·9	67	ENE	Var.	111	4·2	1·6	91	SE	Var.	78	4·1	2·9	101	ESE		20	4·1	1·7	141	NE—SE	
130	6·3	2·6	85	E	Var.	100	6·0	3·0	95	E	SE	43	5·8	2·8	91	NE—SE		7	6·4	3·8	79	..	..
272	5·7	2·2	24	W—N—E		219	5·3	1·3	60	E	Var.	141	6·0	3·8	87	E	Var.	78	6·3	4·9	88	E	SE
211	5·6	1·5	15	Var.		176	5·4	1·0	88	E	Var.	110	5·6	3·0	93	E		35	5·5	3·9	102	N—E—S	
141	4·9	1·0	116	Var.		107	5·5	2·5	99	E	Var.	58	5·3	4·1	94	N—E—S		26	7·3	5·8	90	NE—S	
88	7·2	3·2	309	Var.		50	7·5	1·4	306	W	Var.	12	5·4	2·3	235	..	..	6	3·4	1·3	162	..	..

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	88	6·2	5·7	83	E	NE	82	7·8	7·6	82	E		66	8·1	7·5	58	NE	E
Bahrein	230	6·5	2·7	334	N	Var.	228	6·3	2·9	231	N	Var.	201	6·3	2·3	306	NW	Var.
Muscat	232	3·5	2·2	302	WNW	Var.	237	3·8	2·0	338	NW	Var.	229	5·1	1·4	29	Var.	
Gwador	211	4·5	2·3	3	NE	Var.	210	4·6	2·1	22	Var.		204	4·6	1·3	25	Var.	
Karachi*	300	5·6	2·1	5	NE	SSW	300	4·5	0·8	350	Var.		298	4·7	1·6	30	NE	Var.
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	322	2·8	1·1	301	NW	S
Peshawar*	261	1·8	0·7	299	..	..	264	2·5	1·9	332	W—N		260	4·2	2·9	321	NNW	Var.
Lahore*	407	4·5	2·1	328	NW	Var.	408	4·1	2·6	313	NW	Var.	410	4·9	3·4	309	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	72	4·6	3·6	317	NW	Var.	74	5·8	5·0	313	W—N—E		74	7·7	6·5	317	NW	SE
Ahmedabad	208	5·8	4·5	84	E	Var.	209	4·1	2·9	77	E	Var.	207	3·9	0·7	46	Var.	
Ajmer	..	..	..	..	..	..	206	3·8	0·2	333	Var.		208	4·6	2·6	312	NW	Var.
Agra*	541	4·7	2·1	330	NNW	Var.	543	4·8	3·1	323	NNW	Var.	536	6·5	5·2	318	NW	Var.
Allahabad	147	4·3	2·6	315	NW	Var.	147	5·3	4·2	319	W—N—E		143	7·7	5·4	336	NW	Var.
Patna	206	3·6	1·7	306	NW	Var.	208	4·4	2·7	307	NW	Var.	203	6·9	4·8	302	NW	Var.
Rangpur	28	4·0	2·5	67	ENE	Var.	28	3·9	2·4	60	ENE	Var.	28	4·9	4·2	58	ENE	W
Tezpur	158	4·6	3·8	86	E		152	4·8	3·7	84	E	Var.	139	4·3	2·0	90	E	Var.
Calcutta*	341	5·1	3·9	16	NNE	Var.	340	4·7	3·6	5	N	Var.	312	5·3	3·2	313	NW	Var.
Dacca	198	3·2	1·5	2	N	Var.	194	3·5	1·7	333	N	Var.	185	5·8	3·6	276	NW	Var.
Chittagong	186	3·5	1·7	31	NNE	Var.	186	3·5	0·5	335	NNW	S	170	5·4	3·1	247	Var.	
Akyab*	329	3·5	1·6	56	Var.		327	3·2	1·2	152	SSE	Var.	309	4·5	2·3	200	Var.	
Mandalay	182	2·8	1·3	157	SSE	NNE	176	2·9	0·6	186	S	N	164	4·6	3·3	214	SSW	Var.
Rangoon	197	5·4	3·7	61	N—SE		196	5·0	3·6	100	ESE	Var.	188	5·1	3·4	116	ESE	Var.
Jubbulpore	..	..	..	..	..	..	206	4·8	2·6	27	NNE	Var.	204	5·7	4·1	344	NNW	Var.
Ranchi	..	..	..	..	..	..	30	3·9	3·2	333	NW	N	30	5·7	5·0	319	SW—N	
Sambalpur	144	4·0	2·7	35	NE	Var.	141	4·7	3·0	23	NNE	Var.	138	5·8	3·2	345	NNW	Var.
Poona*	..	..	..	..	..	..	295	5·5	4·0	108	E	SE	286	4·9	2·8	100	NE—S	
Hyderabad	..	..	..	..	..	..	175	6·2	4·6	62	N—SE		152	5·9	4·2	53	NE	Var.
Waltair	202	6·7	5·7	52	NE	Var.	198	6·5	5·6	53	NE	E	180	5·5	3·5	52	NE	Var.
Mangalore	207	4·6	2·4	83	E	Var.	208	4·7	3·4	90	E	Var.	195	5·2	3·8	83	E	Var.
Bangalore*	..	..	..	..	..	..	367	5·3	4·0	65	..	..	330	5·6	3·1	57	ENE	Var.
Madras	255	7·5	5·7	35	NE	Var.	237	7·7	5·8	45	N—E—S		188	6·5	3·3	60	ENE	Var.
Port Blair	251	6·6	4·6	85	NE—SE—SW		216	7·2	5·0	96	E	Var.	150	6·6	4·1	100	E	Var.
Trivandrum	168	3·1	1·1	295	NW	Var.	168	3·8	1·0	304	Var.		140	4·8	1·3	352	Var.	

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—November.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
61	7·8	6·8	50	NE	E	57	6·5	3·9	49	N—E		41	7·2	2·7	67	N—SE		15	5·9	0·5	207	N	Var.
177	7·0	3·6	293	WNW	Var.	138	8·1	5·6	283	SW—NW		81	12·7	11·3	269	SW—NW		21	15·2	13·0	268	S—W—N	
225	5·4	0·7	355	Var.		205	6·6	4·0	272	SW	Var.	134	12·0	10·0	267	SW—NW		25	16·7	15·8	258	SW—NW	
188	5·6	1·4	300	Var.		166	7·2	4·4	278	W	Var.	114	13·0	11·2	270	SW—N		21	18·6	17·3	262	S—NW	
294	5·9	1·7	317	Var.		274	7·8	5·0	285	SW—NW—NE		209	14·1	12·3	277	S—W—N		84	23·2	21·8	273	SW—NW	
321	6·2	4·6	309	SW—N		304	9·1	7·1	295	SW—NW—NE		173	13·8	11·2	279	SW—N		70	21·8	20·8	287	SW—NW	
254	5·1	3·3	304	NW	Var.	245	6·0	4·0	287	SW—N		215	11·8	9·5	285	SW—NW—NE		141	17·8	15·3	283	W	Var.
405	5·9	4·0	303	NW	Var.	396	7·1	5·2	290	SW—N		356	13·9	12·2	280	S—W—N		257	22·3	20·6	278	SW—N	
394	4·2	1·1	317	NW	Var.	381	5·3	1·8	275	NW/W	SSE	323	13·3	11·4	273	S—W—N		210	25·0	22·9	270	SW—NW	
60	7·6	6·1	311	W—N		45	8·7	7·9	289	SW—NW		14	18·2	17·7	276	SW—NW		..	..	..	..	..	..
193	4·9	2·1	297	NW	Var.	173	6·2	4·0	284	SW—N		139	11·6	10·1	273	S—W—N		33	17·0	15·2	265	SW—N	
204	6·0	4·0	297	WNW	Var.	182	9·0	7·0	278	SW—N		114	16·4	13·9	273	SW—NW		21	26·0	24·0	274	W	SW
519	7·2	5·7	300	SW—NW—NE		496	9·3	7·8	286	SW—N		445	16·2	15·3	277	SW—N		353	26·1	24·5	271	SW—N	
113	8·4	6·3	303	SW—N		64	9·7	8·2	291	SW—N		22	15·0	13·7	274	W	NW	4	21·9	21·1	266	..	..
183	10·2	9·5	299	NW	W	168	12·6	11·4	293	W	N	126	18·5	17·6	281	SW—NW		24	24·0	23·0	272	SW—NW	
28	8·3	4·9	284	W—N—E		26	14·0	12·6	286	W—N		7	17·6	16·9	287	..	..	..	..	..	..	..	..
117	5·0	1·1	237	Var.		90	10·2	8·2	267	WSW	E	50	19·3	18·5	273	W	NW	4	29·1	23·0	291	..	..
289	7·0	5·5	283	SW—N		263	9·3	8·4	279	SW—NW		201	14·0	12·9	274	SW—NW		54	16·2	15·2	276	SW—NW	
149	9·0	8·0	280	SW—NW		114	11·6	10·7	277	SW—NW		57	16·1	14·9	273	SW—NW		3	23·5	23·5	256	..	..
137	7·4	6·3	270	S—NW		107	9·4	9·2	271	SW—NW		49	11·3	10·1	273	S—W—N		7	13·4	13·0	270	..	..
278	5·4	3·2	249	WSW	Var.	255	6·5	4·7	268	W	Var.	196	8·9	7·9	273	W	Var.	117	12·8	11·5	271	SW—N	
134	7·3	5·3	256	S—W—N		109	9·2	8·3	275	SW—NW		55	11·2	10·4	273	SW—NW		4	12·8	11·2	288	..	..
159	4·9	2·0	94	Var.		110	4·6	2·0	30	Var.		65	5·2	0·2	172	Var.		12	8·8	4·9	258	SW—NW	
193	6·0	4·1	318	NW	Var.	171	7·8	6·1	293	SW—N		127	12·1	10·5	278	S—NW		17	14·6	13·3	261	SW—NW	
30	9·1	8·4	305	NW	W	30	11·8	10·9	293	W	NW	15	15·4	14·6	276	W	NW	..	..	..	..	..	..
128	5·9	3·2	310	NW	Var.	107	7·0	4·4	293	SW—NW		76	9·5	7·2	282	SW—N		14	16·5	15·6	279	W	NW
272	4·8	1·2	44	NE	Var.	260	5·4	1·4	351	Var.		236	7·1	3·0	290	Var.		167	9·9	6·9	269	W	Var.
142	5·1	3·4	59	NE	Var.	136	5·4	2·7	54	NW—NE—SE		116	5·7	2·0	52	Var.		77	6·4	1·6	242	SW	Var.
150	4·6	2·1	34	Var.		124	4·4	1·3	25	Var.		79	5·1	0·7	322	NW	Var.	25	8·8	5·8	271	W	ESE
176	5·8	4·1	86	E	Var.	145	6·5	4·6	84	ENE	W	60	7·3	5·9	76	N—SE		31	7·3	5·2	91	E	Var.
271	5·5	3·2	71	ENE	Var.	228	5·7	3·3	84	E	NE	169	7·3	5·3	77	E	Var.	101	7·1	3·0	89	SW	Var.
156	5·5	3·3	73	ENE	Var.	132	5·6	3·8	75	E	Var.	81	7·1	4·9	75	E	Var.	31	6·8	3·1	66	NE	E
99	5·4	3·3	95	E	Var.	77	6·0	4·5	87	NE—SE—SW		51	7·3	6·0	83	N—E		21	7·0	4·3	82	NE—SE	
106	5·1	1·3	37	ENE	Var.	66	7·7	2·4	74	SE	Var.	24	5·2	2·8	95	ENE	S	11	6·3	4·0	81	..	.

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX A.—Normal Upper Winds up to

Station.	0·5 km.						1·0 km.						2·0 km.					
	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
Aden	90	6·3	6·0	89	E		76	7·2	6·9	85	E		55	7·2	6·0	64	NE	E
Bahrein	233	8·5	4·5	327	N/NW	Var.	227	7·3	3·7	314	NNW	Var.	193	7·7	5·4	284	WNW	Var.
Muscat	231	4·0	2·3	293	WNW	Var.	229	4·4	2·3	306	NW	Var.	210	5·6	3·1	308	NW	Var.
Gwador	236	4·6	1·5	9	Var.		237	4·8	1·1	349	Var.		225	5·7	3·1	294	W	Var.
Karachi*	310	6·6	4·2	38	W—N—E		308	5·0	2·0	17	Var.		304	5·5	1·8	308	Var.	
Quetta*	..	..	..	..	..	..	..	..	..	..	..	..	314	3·1	0·9	238	S	NW
Peshawar*	288	2·1	0·2	134	..	..	287	2·6	2·1	320	SW—N		287	4·4	2·6	341	N	Var.
Lahore*	418	4·6	2·3	334	NW	Var.	418	4·3	2·0	311	NW	Var.	398	4·5	1·9	285	NW	Var.
Simla*	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Delhi	90	6·2	4·0	324	NW	Var.	90	6·6	5·0	310	NW	Var.	86	7·2	6·0	302	S—W—N	
Ahmedabad	212	5·9	3·5	74	E	Var.	213	4·4	0·7	50	Var.		211	5·8	2·7	261	Var.	
Ajmer	..	..	..	..	..	..	208	4·5	0·2	138	SE	Var.	208	5·4	3·3	278	SW—NW—NE	
Agra*	538	5·3	2·5	340	NW	Var.	540	5·1	3·0	313	NW	Var.	533	6·7	5·1	293	S—W—N	
Allahabad	155	4·1	1·7	315	NW	Var.	155	5·1	3·7	309	NW	Var.	148	8·4	7·8	306	SW—N	
Patna	213	4·0	2·0	302	WNW	ESE	213	4·3	2·4	295	WNW	ESE	211	8·0	6·1	294	NW	Var.
Rangpur	30	4·9	1·7	22	NE	Var.	30	4·7	1·3	28	NE	Var.	27	5·2	1·9	307	W—N—E	
Tezpur	171	4·4	3·8	85	E		170	5·0	4·0	82	E	NE	158	4·9	2·9	84	E/NE	WSW
Calcutta*	363	5·1	4·2	6	N	Var.	362	5·3	4·3	346	NW—NE		332	6·6	5·0	316	SW—NW—NE	
Dacca	215	3·2	2·1	353	N	Var.	215	3·6	1·9	325	NNW	Var.	210	6·7	5·1	289	WNW	Var.
Chittagong	209	3·5	2·6	20	N—SE		209	3·5	0·7	311	NNW	S	200	5·8	3·9	271	W	Var.
Akyab*	353	3·6	2·0	39	N—SE		350	3·5	0·3	221	SSE	NNW	340	4·9	2·2	259	Var.	
Mandalay	207	2·3	0·7	129	NNE	SSE	206	2·4	0·4	158	Var.		203	4·7	4·4	217	SSW	Var.
Rangoon	177	5·1	3·6	38	N—E		177	3·9	2·2	103	ESE	Var.	173	4·7	1·7	152	Var.	
Jubbulpore	..	..	..	..	..	..	213	4·6	1·3	25	Var.		208	6·8	4·8	305	NW	Var.
Ranchi	..	..	..	..	..	..	29	4·6	3·3	318	NNW	Var.	25	9·9	8·2	307	W—N	
Sambalpur	154	3·1	1·8	45	NE	Var.	155	3·6	2·0	359	N	Var.	151	6·5	5·0	327	SW—N	
Poona*	..	..	..	..	..	..	305	5·1	4·0	113	SE	E	302	4·8	2·5	142	NE—SE—SW	
Hyderabad	..	..	..	..	..	..	181	5·6	4·5	99	NE—S		174	5·4	3·4	53	NE	Var.
Waltair	246	5·0	4·6	61	NE	E	211	5·5	4·9	58	N—E		198	5·3	3·5	43	NW—NE—SE	
Mangalore	213	6·0	4·4	86	N—E—S		213	5·2	4·1	92	N—E—S		206	5·6	4·4	89	NE—SE	
Bangalore*	..	..	..	..	..	..	425	5·6	5·2	80	..	..	369	6·0	5·0	77	N—SE	
Madras	271	7·5	7·0	44	N—E		257	7·5	6·9	54	N—E		208	5·7	5·1	70	ENE	Var
Port Blair	257	7·4	6·7	66	N—SE		226	7·4	6·7	77	NE—SE		172	6·6	5·2	90	E	Var.
Trivandrum	198	2·6	0·6	46	NE	Var.	197	3·2	1·4	49	ENE	Var.	179	4·5	1·8	68	E	Var.

* For stations marked with an asterisk, the available data up to the end of 1931 only have been used ;

8 km. above Sea Level over India—December.

3·0 km.						4·0 km.						6·0 km.						8·0 km.					
n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″	n	V	v	D	D′	D″
47	8·0	6·3	69	NE	E	41	8·2	5·2	69	ENE	W	26	11·1	7·4	88	NE—S		5	7·7	6·2	226	..	..
146	9·6	8·1	280	SW—N		109	11·7	10·3	279	SW—N		50	17·8	16·4	278	W	NW	9	24·5	22·6	286	..	..
189	8·2	6·1	294	WNW	Var.	156	10·6	8·8	281	SW—N		81	16·9	15·5	275	SW—N		13	22·4	20·2	284	NW	W
198	8·6	6·9	281	W	Var.	157	12·6	10·9	278	SW—N		75	18·4	16·7	274	SW—N		10	25·3	24·1	292	..	..
290	8·0	5·9	276	W	Var.	264	11·1	9·6	273	SW—N		189	19·0	16·8	273	SW—N		76	23·6	22·3	274	SW—N	
306	6·7	4·3	295	S—W—N		259	10·8	8·3	283	SW—N		115	15·5	14·6	277	SW—N		28	20·7	18·4	282	W—N	
276	4·8	0·9	309	Var.		253	6·1	3·0	265	WNW	Var.	193	13·4	9·5	270	S—W—N		104	19·9	17·7	281	S—W—N	
386	5·9	3·4	262	S—W—N		361	8·6	6·3	264	S—W—N		277	16·5	15·1	272	S—W—N		161	25·8	23·9	275	S—W—N	
387	4·9	0·8	191	SE/S	NW	361	6·7	2·5	246	NW	Var.	258	15·6	13·7	271	S—NW		131	25·1	24·0	270	SW—N	
74	7·4	6·2	283	SW—N		60	11·4	10·3	276	SW—NW		23	18·9	18·0	278	W	SW	..	..	..	..	..	..
194	7·7	5·5	268	SW—NW—NE		165	10·4	8·7	272	S—W—N		99	16·7	15·2	277	SW—NW		15	22·2	21·7	264	SW—NW	
183	8·5	6·7	276	W	Var.	151	12·4	11·0	272	SW—N		81	20·1	17·7	270	SW—NW		9	22·5	21·7	285	..	..
515	8·3	6·9	279	S—W—N		489	11·7	11·0	276	SW—NW		422	20·3	18·8	271	SW—NW		281	28·9	27·4	272	SW—NW	
114	10·1	9·3	295	SW—N		51	11·2	10·4	286	W	NW	16	14·9	14·0	281	..	..	4	20·7	18·5	289	..	..
188	11·3	10·2	294	W	NW	163	14·2	13·4	286	W	NW	104	20·9	19·7	276	SW—NW		15	24·1	22·9	281	W	
25	13·2	12·9	278	W	NW	23	16·9	16·5	276	W		7	17·9	17·2	266	..	..	..	..	..	..	..	..
133	6·2	2·1	269	WSW	ENE	100	13·0	11·3	270	W/SW	E	47	20·4	18·9	270	W	SW	3	18·0	15·9	277	..	..
300	8·5	7·2	289	SW—N		271	11·0	9·7	279	SW—NW		192	16·2	14·6	270	SW—N		45	20·6	18·6	264	SW—NW	
187	11·0	7·9	383	SW—NW		158	15·1	13·9	278	SW—NW		54	19·9	18·2	268	SW—NW		6	27·5	26·5	254	..	..
180	9·2	8·0	281	SW—NW		141	11·7	10·7	277	SW—NW		70	17·1	15·9	276	SW—NW		8	20·0	18·5	273	..	..
320	6·5	4·8	275	W	Var.	304	8·5	7·1	273	S—NW		240	12·9	11·6	273	SW—N		109	18·9	17·1	265	SW—NW	
179	8·0	6·8	265	S—NW		155	12·0	11·2	274	SW—NW		76	16·3	11·9	273	SW—NW		5	27·7	22·4	276	..	..
139	4·7	1·2	311	W	Var.	116	5·6	2·1	246	NW	Var.	78	8·0	4·1	290	Var.		9	8·4	5·0	220	..	..
191	8·9	7·3	293	S—W—N		166	11·3	9·8	286	S—W—N		97	16·0	14·6	278	SW—N		13	21·9	21·0	263	W	SW
25	10·4	9·7	285	SW—NW		17	10·1	9·6	276	SW—NW		4	15·7	15·5	262	..	..	..	..	..	..	..	..
140	8·1	6·6	307	SW—N		109	10·3	8·6	291	S—W—N		62	14·1	12·8	280	S—NW		29	18·6	17·8	269	SW—NW	
293	5·5	0·9	256	Var.		285	7·1	3·4	278	W	Var.	252	11·1	7·8	273	W	Var.	153	14·4	12·4	269	S—NW	
167	5·2	2·0	35	Var.		157	6·5	2·4	347	NW	Var.	129	7·9	4·3	291	W	Var.	77	10·0	7·6	273	S—W—N	
177	5·1	1·6	16	NE	Var.	141	5·6	1·8	314	Var.		95	9·0	5·5	287	SW—NW—NE		20	9·2	7·0	264	SW—NW	
192	6·4	4·2	81	E	Var.	161	7·7	4·6	76	NE—SE		80	7·1	2·9	52	E	Var.	24	8·0	3·1	332	Var.	
348	5·7	3·8	81	E	Var.	318	6·2	2·5	334	E	Var.	252	7·2	2·5	83	E	Var.	168	7·8	1·0	279	Var.	
175	5·6	3·1	67	E	Var.	149	5·4	2·5	71	E	Var.	98	6·3	1·0	80	E	Var	40	6·7	1·6	255	SW	Var.
118	5·7	3·8	94	E	Var.	93	5·5	3·7	89	NE—S		66	7·0	4·9	80	NE—SE		25	7·5	3·0	67	N—E—S	
150	5·4	2·9	82	E	Var.	112	6·9	4·9	86	E	Var.	52	8·6	6·7	84	ESE	Var.	14	12·7	10·9	85	NE—SE	

for the remaining stations, data up to the end of 1934 have been used.

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

JANUARY.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	167	18	3	2	1	1	20	38	17	..	80	2	..	..	1	1	15	66	13	1	78	..	..	..	..	..	23	68	8	..
Muscat	1928—'35	156	7	2	12	7	4	11	23	31	2	53	..	..	..	1	7	16	59	16	..	115	..	..	..	..	..	9	79	12	..
Gwador	1928—'35	137	..	..	5	18	19	29	29	..	..	49	..	..	..	1	..	11	79	8	..	121	..	..	..	..	..	6	89	5	..
Karachi	1926—'35	131	1	4	2	..	1	22	64	7	..	69	..	..	..	..	..	10	81	8	..	209	..	..	..	..	..	7	80	12	..
Quetta	1926—'35	226	1	..	1	..	4	33	42	19	..	59	1	..	..	..	3	27	49	20	..	98	..	..	1	..	1	11	68	18	..
Peshawar	1926—'35	223	5	16	13	14	20	17	7	7	..	354	1	3	5	6	11	37	29	8	..	386	..	1	..	1	3	22	60	12	..
Lahore	1926—'35	117	1	3	1	9	25	33	23	5	..	127	1	..	1	1	14	35	47	2	..	142	..	..	..	..	1	21	66	12	..
Simla	1926—'28	29	..	..	2	34	4	29	20	10	..	37	..	..	..	9	10	26	42	12	..	30	..	..	..	..	..	12	80	8	..
Ahmedabad	1929—'35	36	..	..	..	..	10	61	16	12	..	25	..	..	..	..	3	29	68	1	..	88	..	..	..	..	..	16	75	8	..
Ajmer	1929—'34	45	1	4	1	..	4	58	25	6	..	52	..	..	..	..	8	50	40	1	..	119	..	..	..	..	..	19	61	20	..
Agra	1926—'35	120	3	..	2	3	8	49	29	6	..	94	..	..	..	1	3	30	63	4	..	216	..	..	..	..	..	12	74	14	..
Allahabad	1931—'35	29	..	..	..	5	7	44	36	8	..	19	..	..	..	..	..	19	81	..	..	45	..	..	..	..	..	26	73	1	..
Patna	1929—'35	64	1	3	6	2	2	17	48	10	12	48	..	..	..	..	..	14	85	1	..	169	..	..	..	..	..	24	71	5	..
Tezpur	1929—'35	134	1	9	13	2	3	30	34	4	4	37	..	..	..	2	2	15	63	18	..	27	..	..	2	..	..	13	79	6	..
Calcutta	1926—'35	100	8	1	1	..	5	22	37	16	10	28	..	..	..	..	..	29	58	12	2	108	1	..	..	..	1	33	55	10	1
Dacca	1929—'35	74	4	5	1	..	2	15	31	34	8	38	..	..	..	..	..	24	70	6	..	38	..	..	..	..	..	11	83	6	..
Chittagong	1929—'35	35	4	1	3	..	5	24	38	25	..	32	4	..	..	..	..	20	58	18	..	52	..	..	..	1	2	31	57	8	..
Akyab	1926—'35	37	8	5	16	3	3	27	17	21	..	62	..	..	..	..	1	43	50	6	..	97	..	..	..	..	1	26	66	7	..
Mandalay	1929—'35	33	..	..	..	..	17	46	33	5	..	27	..	..	..	..	8	48	42	2	..	99	..	..	..	..	..	18	81	..	..
Rangoon	1929—'35	87	2	9	9	12	23	15	19	7	2	13	..	..	..	19	3	53	..	..	25	53	..	..	..	..	3	38	26	14	17
Jaipur	1926—'35	85	3	6	3	2	9	32	40	6	..	110	1	1	1	2	4	33	54	5	..	144	..	..	1	..	2	26	63	8	..
Jubbulpore	1929—'35	98	1	3	1	..	1	39	49	7	..	44	..	..	..	..	..	30	66	4	..	115	..	..	..	..	..	16	71	13	..
Sambalpur	1931—'35	44	19	21	1	4	3	11	34	8	..	16	..	..	..	..	..	49	43	8	..	36	..	..	..	..	..	19	81	..	..
Bombay	1926—'35	55	2	6	6	4	17	45	14	5	..	55	..	..	2	9	13	48	23	1	4	219	..	..	1	6	7	42	37	6	..
Poona	1926—'35	106	..	2	3	16	13	36	21	6	..	52	4	1	1	1	2	44	38	8	..	196	..	..	..	..	..	46	50	2	..
Hyderabad	1930—'35	65	11	7	18	37	8	7	11	1	..	10	1	..	..	..	11	34	50	4	..	63	..	..	..	..	6	44	49	1	..
Waltair	1929—'35	89	8	13	22	5	10	20	15	8	..	36	..	..	5	17	4	30	40	3	..	85	..	..	..	..	4	39	55	3	..
Mangalore	1929—'35	45	2	17	29	13	..	11	15	13	..	55	3	5	25	26	8	22	9	1	..	118	..	3	7	10	9	23	37	10	..
Bangalore	1926—'35	289	1	12	50	23	3	6	3	1	..	35	6	10	14	26	14	14	11	4	..	146	6	1	..	14	14	36	23	5	..
Madras	1926—'35	567	5	54	31	7	2	1	1	..	..	67	3	9	15	28	16	17	9	1	..	158	..	..	2	13	26	37	16	3	2
Port Blair	1927—'35	432	2	39	52	5	..	..	..	1	..	38	..	11	27	17	2	13	20	4	6	96	..	..	5	26	31	20	9	1	7
Kodaikanal	1926—'35	246	9	14	31	25	6	3	5	7	1	39	3	13	11	45	15	4	1	1	6	116	1	2	12	32	22	21	5	2	3
Trivandrum	1926—'35	145	4	42	22	9	3	9	4	7	..	89	3	35	31	13	9	7	..	1	..	73	1	17	28	21	15	11	2	5	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

FEBRUARY.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	118	14	4	..	3	2	20	42	15	..	62	..	..	..	..	2	40	56	2	..	53	..	..	..	..	..	27	66	7	..
Muscat	1928—'35	106	4	1	9	2	1	10	46	29	..	42	..	2	..	..	..	25	62	11	..	62	..	..	..	..	..	10	79	11	..
Gwador	1928—'35	102	1	3	11	11	20	28	23	4	..	50	..	2	..	..	..	19	67	12	..	90	..	..	..	..	..	4	92	4	..
Karachi	1926—'35	87	1	1	1	1	1	14	62	17	1	78	1	..	..	..	..	8	79	11	..	161	1	..	..	..	..	8	79	11	1
Quetta	1926—'35	156	2	..	..	1	3	26	53	16	..	55	..	..	..	..	1	30	57	11	..	71	2	..	..	..	..	10	71	17	..
Peshawar	1926—'35	241	8	7	13	15	15	21	10	11	..	323	2	..	1	..	7	15	57	18	..	376	2	1	..	7	15	57	18	..	..
Lahore	1926—'35	90	3	2	1	10	19	27	23	15	..	142	1	1	..	..	4	45	43	8	..	151	1	..	..	1	2	20	61	15	..
Simla	1926—'28	40	..	..	..	14	24	25	31	6	..	41	6	..	..	8	5	22	41	19	..	35	4	..	..	..	..	6	64	25	..
Ahmedabad	1929—'35	38	4	..	..	..	5	46	25	20	..	35	..	..	..	..	..	46	54	..	..	82	1	..	..	..	..	8	71	19	..
Ajmer	1929—'34	47	1	1	..	..	10	39	40	9	..	32	..	..	..	..	6	35	57	2	..	113	..	..	..	..	1	9	71	19	..
Agra	1926—'35	127	6	..	1	1	7	33	38	15	..	83	..	..	..	1	1	34	52	11	..	183	2	..	..	1	1	6	78	13	..
Allahabad	1931—'35	44	7	2	7	3	5	15	52	8	..	23	..	..	..	..	..	25	75	..	..	27	..	..	..	..	4	34	53	8	..
Patna	1929—'35	45	1	2	10	5	..	19	55	8	..	67	..	..	..	..	..	31	65	4	..	118	..	..	..	..	..	12	74	14	..
Tezpur	1929—'35	92	..	..	12	7	7	29	43	..	..	55	3	..	..	..	1	13	72	6	3	21	4	4	..	..	..	5	67	17	3
Calcutta	1926—'35	146	6	1	3	3	4	22	43	14	3	39	..	..	..	..	..	44	52	..	4	50	3	..	..	..	..	35	60	2	..
Dacca	1929—'35	79	2	3	1	1	10	22	46	12	2	46	..	4	..	..	..	24	58	14	..	24	..	..	..	..	..	12	64	24	..
Chittagong	1929—'35	36	5	..	..	3	9	13	48	23	..	35	..	..	..	..	..	15	71	14	..	22	..	..	..	..	..	8	91	1	..
Akyab	1926—'35	49	5	3	..	3	9	32	41	4	..	30	..	..	..	..	..	34	61	5	..	37	..	..	..	..	..	40	55	5	..
Mandalay	1929—'35	40	..	..	..	..	8	49	33	9	1	51	..	..	..	..	3	22	73	2	..	52	..	..	..	..	..	22	76	2	..
Rangoon	1929—'35	56	..	5	3	8	20	38	20	6	..	14	..	..	..	5	5	55	35	..	..	41	..	..	..	..	11	46	30	11	1
Jaipur	1926—'35	61	3	..	1	2	11	36	37	11	..	88	..	..	..	..	3	31	63	2	..	115	2	..	..	..	1	19	63	16	..
Jubbulpore	1929—'35	65	3	2	2	..	3	32	53	6	..	64	3	..	..	..	..	14	77	6	..	75	..	..	..	..	..	15	75	13	..
Sambalpur	1931—'35	36	..	..	3	..	7	24	57	9	..	21	..	..	..	..	..	13	87	..	..	31	..	..	..	..	..	37	51	12	..
Bombay	1926—'35	66	5	4	8	9	20	19	22	13	..	28	4	5	..	..	30	44	16	..	..	90	3	..	2	8	5	33	32	17	..
Poona	1926—'35	75	1	1	2	6	28	36	20	5	..	38	..	..	..	4	7	39	36	15	..	67	1	..	..	..	7	22	50	26	..
Hyderabad	1930—'35	40	3	..	2	15	19	29	19	13	..	5	..	..	..	..	29	37	25	9	..	27	..	..	3	2	3	28	63	2	..
Waltair	1929—'35	85	3	5	7	13	20	38	10	4	..	36	5	1	..	..	3	25	40	27	..	39	..	..	..	..	..	36	63	..	..
Mangalore	1929—'35	62	8	9	7	10	6	10	23	27	..	32	2	4	4	39	31	6	9	4	..	48	..	..	9	16	18	23	23	11	1
Bangalore	1926—'35	178	3	10	31	32	3	13	5	3	..	25	..	14	12	23	8	34	4	5	..	69	2	4	4	15	6	44	15	9	..
Madras	1926—'35	340	2	21	40	22	8	4	1	1	..	46	1	3	10	7	10	42	20	6	2	102	..	..	1	6	22	39	22	4	6
Port Blair	1927—'35	220	5	39	34	9	3	4	5	2	..	59	..	..	8	6	27	29	16	3	9	85	4	..	4	13	25	23	19	..	11
Kodaikanal	1926—'35	167	14	13	20	20	5	4	7	16	..	23	1	6	15	31	12	25	3	9	..	97	1	3	9	19	24	21	18	3	2
Trivandrum	1926—'35	105	5	35	22	5	7	13	2	11	..	58	5	13	21	26	3	6	13	10	2	70	8	3	28	32	13	6	10	..	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

MARCH.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	105	10	..	4	..	2	25	53	5	..	76	..	..	..	..	..	25	64	12	..	64	4	..	..	..	..	28	61	6	..
Muscat	1928—'35	55	4	2	4	..	3	26	46	15	..	54	..	..	..	..	2	12	81	5	..	30	1	..	..	..	..	20	68	12	..
Gwador	1928—'35	74	..	..	2	5	17	29	46	1	..	29	..	..	..	..	..	26	62	12	..	107	..	..	..	..	..	10	79	11	..
Karachi	1926—'35	74	..	..	..	1	..	11	75	12	1	54	..	..	..	..	..	25	75	..	..	174	..	..	..	..	..	15	78	5	1
Quetta	1926—'35	188	1	..	1	1	7	37	44	9	2	59	1	6	1	1	3	35	50	4	..	72	3	..	..	1	1	17	56	22	..
Peshawar	1926—'35	245	7	6	9	8	18	26	17	9	..	330	2	2	1	5	7	39	36	7	..	467	..	..	2	2	3	18	61	13	..
Lahore	1926—'35	62	..	2	3	11	31	29	20	4	..	75	1	2	..	1	12	41	43	1	..	180	..	..	..	..	1	24	64	11	..
Simla	1926—'28	47	..	..	2	15	17	23	42	1	..	26	..	..	..	12	13	32	32	9	..	23	..	..	..	..	..	15	84	1	..
Ahmedabad	1929—'35	8	..	..	..	5	5	41	43	5	..	16	..	..	..	3	3	24	71	..	..	54	4	..	..	..	..	21	60	14	..
Ajmer	1929—'34	27	..	..	..	..	10	46	35	9	..	23	..	..	..	..	1	52	47	..	..	101	..	..	..	..	..	20	71	9	..
Agra	1926—'35	79	2	..	2	..	7	35	45	9	..	77	4	..	..	..	..	31	53	11	..	181	..	..	..	..	..	19	74	7	..
Allahabad	1930—'35	28	..	..	..	..	3	7	87	3	..	23	..	..	5	..	6	31	59	..	..	50	..	..	..	..	1	29	71	..	..
Patna	1929—'35	25	..	..	9	7	..	27	35	21	..	45	1	..	1	1	..	17	77	1	..	89	2	..	..	..	..	18	72	8	..
Tezpur	1929—'35	108	..	2	3	2	3	38	46	1	4	33	..	..	..	..	..	14	59	13	14	22	..	..	..	..	..	23	45	28	3
Calcutta	1926—'35	152	1	1	1	1	9	41	33	13	1	36	..	..	..	..	..	18	55	13	14	57	3	6	..	..	..	35	45	4	7
Dacca	1929—'35	124	1	1	1	3	20	40	23	7	3	24	..	..	..	4	4	10	60	23	..	9	..	..	..	..	..	17	83	..	..
Chittagong	1929—'35	74	1	..	1	3	12	39	36	17	..	27	..	..	..	2	4	18	64	13	..	29	..	..	..	..	..	24	66	10	..
Akyab	1926—'35	110	8	20	2	3	6	19	31	11	..	39	8	20	2	3	6	19	31	11	..	45	..	..	..	..	4	21	74	2	..
Mandalay	1929—'35	45	..	..	..	..	..	50	44	6	..	44	..	..	..	..	..	29	71	..	..	33	..	..	..	..	..	21	70	8	..
Rangoon	1929—'35	87	..	3	5	11	16	31	26	8	1	21	2	20	..	..	1	43	34	..	..	34	..	..	..	..	3	39	46	8	2
Jaipur	1926—'35	50	1	..	..	..	7	37	43	11	..	69	1	3	1	..	4	21	63	7	..	112	..	..	..	..	3	32	55	10	..
Jubbulpore	1929—'35	34	..	..	..	..	1	28	61	9	..	73	..	..	..	..	..	24	67	9	..	55	..	..	..	..	..	17	77	6	..
Sambalpur	1931—'35	27	..	..	..	10	..	18	69	3	..	35	..	..	..	..	3	15	62	19	..	23	..	..	..	..	..	41	59	..	..
Bombay	1926—'35	101	20	1	6	13	18	12	12	17	..	44	..	..	5	8	30	32	15	9	..	66	..	..	4	8	8	28	35	17	..
Poona	1926—'35	93	3	11	8	11	25	25	15	4	..	58	..	1	7	2	12	49	20	9	..	69	..	..	..	..	..	47	41	12	..
Hyderabad	1930—'35	48	..	9	18	21	15	15	14	8	..	25	23	5	..	..	8	14	21	30	..	18	..	..	..	..	26	61	11	1	..
Waltair	1929—'35	71	3	3	..	1	13	68	11	..	..	35	35	3	..	..	..	8	18	37	..	42	..	..	..	..	..	66	34	..	..
Mangalore	1929—'35	137	15	12	10	6	9	13	10	24	..	46	1	29	21	26	4	13	2	4	..	57	11	6	10	26	22	23	3	1	..
Bangalore	1926—'35	189	3	14	22	21	6	14	10	10	..	29	11	13	22	12	4	19	9	9	..	107	..	7	6	19	22	31	8	7	..
Madras	1926—'35	235	1	7	18	22	35	16	1	1	..	29	6	..	11	33	14	21	9	7	..	173	..	..	5	14	25	35	13	3	6
Port Blair	1926—'35	234	2	26	46	11	4	2	3	5	..	26	1	13	14	29	27	7	5	3	..	147	4	3	5	25	28	15	9	3	6
Kodaikanal	1926—'35	252	21	32	25	8	5	1	3	6	..	17	5	10	25	18	5	33	..	3	..	134	..	4	9	29	19	27	9	2	1
Trivandrum	1926—'35	171	14	19	9	7	4	10	10	29	..	69	..	21	29	25	5	8	6	4	..	101	..	10	24	43	13	3	2	6	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

APRIL.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	91	..	..	..	2	3	43	48	4	..	94	..	..	..	..	3	40	53	3	..	70	..	..	..	..	2	40	46	13	..
Muscat	1928—'35	51	1	3	..	3	1	23	47	23	..	57	..	..	..	..	1	26	54	19	..	123	1	..	..	..	..	29	58	12	..
Gwador	1928—'35	78	..	..	7	8	10	35	39	2	..	37	..	..	..	..	..	18	76	6	..	113	..	..	..	..	1	20	67	13	..
Karachi	1926—'35	117	..	..	..	..	..	15	79	5	..	58	1	1	..	..	..	9	78	4	6	202	1	..	..	..	..	15	76	7	1
Quetta	1926—'35	227	2	..	..	..	7	35	43	12	..	55	2	..	..	..	8	33	43	13	..	86	3	..	..	..	8	17	51	21	..
Peshawar	1926—'35	331	5	6	8	9	16	30	22	6	..	366	1	1	..	3	11	36	39	0	..	470	2	1	2	1	3	17	57	18	..
Lahore	1926—'35	82	1	1	..	3	15	36	32	12	..	120	2	..	1	2	7	39	42	6	..	167	2	1	..	1	4	31	49	11	..
Simla	1926—'28	55	7	..	..	0	20	29	19	5	11	29	..	..	..	1	14	27	50	8	..	51	..	..	1	2	2	13	72	7	4
Ahmedabad	1929—'35	66	1	1	..	1	4	31	51	11	1	29	..	..	..	..	12	42	46	..	..	65	4	..	..	..	2	27	54	13	..
Ajmer	1929—'34	66	2	..	..	..	3	34	51	9	..	57	..	..	..	..	6	35	51	9	..	107	..	..	..	..	3	15	70	11	..
Agra	1926—'35	113	1	..	..	..	5	21	61	11	1	82	..	..	..	..	1	26	53	10	..	182	..	..	..	..	1	12	73	13	..
Allahabad	1930—'35	58	2	2	2	..	1	19	68	7	..	30	..	..	..	..	..	19	76	5	..	65	..	..	..	..	..	15	77	8	..
Patna	1929—'35	46	..	3	9	8	..	5	56	18	..	57	..	..	..	..	..	23	74	3	..	133	..	..	..	..	2	32	60	5	..
Tezpur	1929—'35	171	..	..	4	2	4	24	61	2	1	48	..	..	..	..	1	17	79	4	..	25	..	..	..	..	..	29	71	..	..
Calcutta	1926—'35	290	1	1	..	1	21	40	16	9	1	43	..	..	..	1	1	40	48	6	4	08	..	2	..	..	..	36	47	11	4
Dacca	1928—'35	199	1	..	..	2	21	50	22	3	1	56	..	..	..	..	3	34	53	11	..	22	..	..	..	4	3	32	53	8	..
Chittagong	1929—'35	184	1	..	..	1	28	50	13	7	..	32	..	..	..	..	..	44	48	8	..	18	..	..	..	..	10	26	59	5	..
Akyab	1926—'35	269	5	2	2	1	7	31	33	20	..	82	1	..	..	..	2	28	52	16	..	72	3	..	..	..	..	22	62	11	1
Mandalay	1929—'35	157	..	..	..	..	2	42	50	5	..	81	..	..	..	..	..	30	64	6	..	79	..	..	..	..	..	14	75	11	..
Rangoon	1929—'35	205	1	..	2	6	9	28	43	11	..	13	..	..	..	4	8	50	37	..	..	54	..	..	..	1	26	27	37	6	2
Jaipur	1926—'35	106	4	..	..	2	3	25	44	21	..	93	1	..	1	2	3	27	53	9	5	122	..	..	1	3	3	21	57	15	..
Jubbulpore	1929—'35	108	..	..	1	..	4	9	68	18	..	90	..	..	..	..	2	21	67	11	..	79	1	..	..	..	2	35	52	9	..
Sambalpur	1931—'35	69	1	..	..	1	1	6	62	29	..	28	..	..	..	..	3	28	43	27	..	30	..	..	..	..	..	47	51	2	..
Bombay	1926—'35	272	13	4	4	6	11	23	20	19	..	58	1	4	3	10	8	36	31	9	..	75	3	4	2	4	7	38	33	0	..
Poona	1926—'35	154	3	14	12	10	15	18	19	9	1	101	3	4	11	16	16	35	12	4	..	56	..	1	..	2	7	26	50	14	..
Hyderabad	1930—'35	83	9	8	7	11	8	14	24	19	..	49	20	16	9	4	5	9	8	30	..	51	1	1	3	..	3	48	35	10	..
Waltair	1929—'35	146	1	3	3	1	6	75	0	3	..	91	8	4	..	..	3	13	26	41	5	79	1	..	..	..	8	27	53	11	..
Mangalore	1920—'35	251	11	9	4	2	4	10	23	38	..	94	4	36	30	10	3	7	2	6	2	85	6	9	14	13	15	28	10	4	..
Bangalore	1926—'35	409	5	16	19	11	6	18	18	7	..	60	3	34	20	13	6	15	7	3	..	116	1	11	6	17	17	24	13	11	..
Madras	1926—'35	265	2	6	0	20	37	23	2	2	1	81	12	14	7	7	8	20	11	9	..	233	..	2	2	9	22	38	17	5	5
Port Blair	1926—'35	323	9	14	25	10	6	10	15	11	..	50	6	..	9	12	26	30	10	6	2	135	..	2	12	28	17	23	7	..	12
Kodaikanal	1926—'35	358	15	39	22	12	1	..	2	7	1	62	12	15	15	13	8	6	13	4	13	147	2	6	7	37	22	16	8	2	1
Trivandrum	1926—'35	317	9	13	7	4	1	3	18	46	..	76	14	11	27	9	7	7	4	20	..	77	5	11	26	29	6	7	5	12	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

MAY.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	30	..	..	..	3	7	66	23	2	..	59	..	..	..	3	3	47	44	3	..	58	..	..	..	..	3	47	48	2	..
Muscat	1928—'35	95	..	6	6	..	..	32	51	3	..	17	..	..	..	..	..	52	48	..	..	59	..	..	..	..	..	50	43	6	..
Gwador	1928—'35	107	..	..	..	2	18	43	36	..	..	11	12	8	17	..	4	4	42	..	17	64	..	..	..	..	..	18	70	12	..
Karachi	1926—'35	310	..	1	..	..	..	12	84	3	..	25	3	5	..	..	..	12	49	21	10	68	..	..	..	..	1	11	74	12	2
Quetta	1926—'34	163	3	1	..	1	3	19	48	24	..	38	8	2	..	1	4	33	39	13	..	52	1	..	1	1	..	41	37	18	..
Peshawar	1926—'35	231	3	6	4	7	10	24	31	17	..	321	1	1	4	3	5	30	45	11	..	339	1	1	1	1	3	19	57	15	..
Lahore	1926—'35	52	2	2	..	4	10	32	34	17	..	87	3	1	1	3	5	20	48	15	..	113	2	..	7	..	1	25	57	9	..
Simla	1926—'28	52	..	3	1	30	15	23	21	6	1	54	2	..	1	3	..	17	37	33	3	18	..	..	..	..	5	16	72	2	5
Ahmedabad	1928—'35	118	1	3	..	1	2	32	50	7	..	13	3	17	..	..	8	28	42	3	..	15	4	..	..	..	..	32	54	8	..
Ajmer	1928—'34	72	4	2	1	3	2	23	37	23	4	31	4	2	..	2	..	18	51	18	4	30	..	3	..	..	..	13	75	11	..
Agra	1926—'35	147	1	..	1	2	2	21	44	28	..	87	..	..	..	3	5	18	51	19	3	86	..	..	..	..	1	22	73	11	..
Allahabad	1930—'35	49	3	1	2	1	..	19	51	23	..	42	..	..	..	..	..	27	52	19	2	31	..	..	..	..	4	27	58	12	..
Patna	1928—'35	86	2	2	26	13	..	5	34	18	..	65	2	..	2	2	2	11	62	15	3	36	3	..	..	..	4	58	26	6	2
Tezpur	1929—'35	166	1	1	11	3	4	35	37	4	1	67	1	1	11	3	4	35	37	4	1	29	..	..	..	..	..	41	54	4	..
Calcutta	1926—'35	389	1	2	3	5	39	34	10	5	1	31	..	..	..	..	..	48	26	18	9	77	3	2	1	2	20	27	22	4	17
Dacca	1928—'35	311	..	..	2	6	33	45	9	3	1	41	1	1	1	1	2	11	56	31	..	15	13	..	4	4	10	31	21	17	..
Chittagong	1929—'35	136	2	2	1	4	37	47	6	3	..	22	..	..	7	..	13	17	32	27	4	8	..	..	..	..	..	25	73	..	..
Akyab	1926—'35	274	3	1	2	7	10	30	32	15	..	73	5	9	4	5	6	17	33	18	2	110	5	..	8	3	11	13	34	19	7
Mandalay	1929—'35	126	3	3	1	2	23	31	26	11	..	105	..	..	1	..	7	47	39	8	..	121	2	1	..	2	8	24	44	7	10
Rangoon	1929—'35	168	2	1	1	5	13	31	36	11	..	16	1	9	10	10	7	23	35	5	..	52	7	7	15	16	4	6	18	24	1
Jaipur	1926—'35	111	10	1	1	1	9	17	36	25	2	87	1	..	..	..	4	20	42	28	10	46	..	..	..	..	4	21	55	18	..
Jubbulpore	1929—'35	93	10	..	..	..	..	16	41	32	..	91	11	..	..	..	1	20	40	28	..	59	5	..	..	4	2	28	46	15	..
Sambalpur	1931—'35	36	4	7	2	3	..	10	26	49	..	24	..	..	..	..	..	25	43	32	..	29	..	..	1	11	4	48	26	10	..
Bombay	1926—'35	465	11	2	5	1	6	13	30	29	..	38	15	8	10	11	31	23	3	3	..	78	5	6	7	27	9	7	20	18	..
Poona	1926—'35	148	6	11	6	10	10	10	29	18	..	64	4	6	16	27	15	18	8	1	7	90	..	3	16	18	18	28	12	4	1
Hyderabad	1930—'35	80	19	20	17	9	1	5	10	17	..	35	8	37	20	1	1	10	5	17	..	59	4	5	14	13	20	27	7	11	..
Waltair	1929—'35	169	4	2	2	1	7	65	16	3	..	97	24	27	8	4	1	5	8	23	..	56	1	9	9	13	8	22	27	12	..
Mangalore	1929—'35	7	6	4	3	1	4	6	24	52	..	95	6	28	39	12	3	6	3	4	..	6	2	16	44	11	12	11	3	1	1
Bangalore	1926—'35	276	8	19	13	7	4	13	25	11	..	86	6	26	14	11	7	16	13	5	..	174	8	18	17	21	7	18	7	9	..
Madras	1926—'35	154	5	9	9	9	28	23	6	10	..	142	12	24	19	5	9	14	10	5	2	289	4	7	22	19	11	11	7	6	10
Port Blair	1926—'35	286	2	2	9	8	4	33	35	6	..	68	5	12	13	7	9	24	14	10	4	130	8	9	25	23	7	6	6	5	9
Kodaikanal	1926—'35	272	15	30	20	8	4	2	11	9	..	89	5	26	15	11	3	10	13	7	9	136	4	15	21	21	13	13	5	2	4
Trivandrum	1926—'35	293	7	3	..	..	1	3	26	59	..	72	13	17	10	2	1	17	23	17	..	66	6	4	20	38	1	22	9	1	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

JUNE.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Muscat	1928—'35	13	..	17	19	2	..	18	23	24	..	50	12	12	46	7	14	2	2	4	..	28	..	22	49	21	..	7	..	..	..
Gwador	1928—'35	203	..	1	5	22	20	27	23	1	..	28	5	29	43	1	..	3	6	8	3	11	7	11	48	27	..	..	..	7	..
Karachi	1926—'35	507	1	2	3	1	2	18	71	2	..	33	10	28	29	3	..	4	15	7	3	41	1	17	38	9	16	5	9	1	6
Quetta	1926—'34	108	10	7	2	2	4	18	35	24	..	13	17	17	..	..	..	16	34	17	..	3	..	..	..	..	..	17	50	33	..
Peshawar	1926—'35	168	3	2	1	4	9	35	31	15	..	306	3	2	2	..	3	33	44	13	..	104	6	..	1	..	3	29	48	13	..
Lahore	1926—'35	45	7	10	10	8	15	20	20	9	1	65	6	2	..	1	3	31	41	18	1	18	..	..	3	14	..	19	46	18	..
Simla	1926—'27	52	4	..	..	2	5	11	41	33	4	32	..	..	..	1	5	27	50	17	..	12	..	..	..	..	..	31	64	5	..
Ahmedabad	1928—'35	303	1	2	1	3	10	33	43	5	..	27	7	6	15	41	12	10	6	..	3	11	..	12	57	11	..	7	7	..	7
Ajmer	1928—'34	119	14	9	4	2	5	21	30	13	..	59	8	11	2	9	7	20	28	15	..	25	11	8	13	20	3	17	19	5	..
Agra	1926—'35	207	8	7	12	4	2	8	31	28	..	105	4	6	4	6	1	12	49	17	..	38	3	16	23	5	13	5	11	22	1
Allahabad	1930—'35	128	6	11	18	5	1	13	28	21	..	48	10	2	14	1	..	28	39	5	..	29	9	5	21	19	..	6	39	1	..
Patna	1928—'35	264	4	8	41	15	3	5	14	9	1	123	5	6	9	17	3	19	26	17	..	137	4	4	11	19	11	19	14	8	11
Tezpur	1929—'35	137	..	3	8	7	5	37	35	3	3	46	1	13	13	1	..	41	25	5	..	31	2	2	16	..	..	12	51	7	5
Calcutta	1926—'35	435	2	2	8	21	31	23	8	8	1	62	6	..	13	19	3	13	24	5	18	83	13	10	36	7	5	6	15	3	7
Dacca	1928—'35	336	..	1	3	21	47	24	3	1	1	37	..	3	20	14	11	24	16	3	9	23	..	1	14	7	20	23	21	10	3
Chittagong	1929—'35	155	..	..	2	19	60	17	1	1	..	18	6	5	18	27	15	5	10	13	..	24	..	5	25	13	9	3	12	3	28
Akyab	1926—'35	320	1	3	9	16	32	21	11	4	..	88	5	15	7	22	11	22	9	8	..	72	7	14	29	15	8	9	8	2	9
Mandalay	1929—'35	250	..	..	..	4	50	35	7	2	..	141	5	5	5	7	12	29	24	9	2	145	5	27	18	11	6	9	9	4	11
Rangoon	1929—'35	204	..	..	1	8	31	42	17	..	1	35	..	..	..	5	7	46	26	6	10	16	..	13	19	6	3	7	40	13	..
Jaipur	1926—'35	110	19	5	4	3	4	13	29	21	2	75	15	6	3	8	4	15	27	20	3	18	11	9	6	6	9	14	7	23	15
Jubbulpore	1929—'35	179	15	8	4	2	3	10	31	26	..	176	12	10	7	3	6	11	30	21	..	95	2	11	28	11	12	15	16	3	2
Sambalpur	1930—'35	141	7	9	7	5	3	15	26	27	..	21	13	11	12	..	10	4	32	20	..	31	1	9	44	25	1	2	14	6	..
Bombay	1926—'35	624	1	1	1	3	11	41	33	8	..	90	11	15	18	15	8	14	10	7	1	72	5	11	23	32	3	13	8	3	..
Poona	1926—'35	527	1	2	4	3	3	23	55	10	..	149	4	14	25	20	7	8	13	6	3	120	3	18	43	25	1	4	1	2	1
Hyderabad	1930—'35	122	8	2	5	3	..	11	45	26	..	56	5	17	25	9	5	12	19	7	..	58	3	26	44	7	5	2	5	5	..
Waltair	1929—'35	138	4	8	1	..	5	39	30	14	..	115	12	16	5	3	1	5	24	27	8	91	5	23	51	14	..	..	..	2	3
Mangalore	1928—'35	298	1	1	..	1	3	14	50	28	3	62	..	22	16	15	15	6	11	7	9	38	5	23	38	11	3	9	7	1	3
Bangalore	1926—'35	541	..	..	..	..	..	27	67	9	..	50	..	14	5	21	5	9	30	15	..	70	1	23	29	15	7	11	7	7	..
Madras	1926—'35	212	3	2	2	1	1	12	57	22	..	198	7	13	9	2	5	12	35	16	2	235	2	17	62	7	2	2	3	3	3
Port Blair	1926—'35	468	..	..	..	1	2	68	28	1	..	76	4	7	23	15	12	15	13	1	11	84	..	10	57	15	2	1	2	1	13
Kodaikanal	1926—'35	297	3	2	2	4	2	5	57	24	..	100	2	8	11	6	4	11	27	24	7	85	1	13	50	21	2	..	1	3	7
Trivandrum	1926—'35	242	2	1	..	2	..	3	38	53	2	85	18	9	3	..	1	6	19	44	..	44	12	13	41	19	1	3	4	7	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

JULY.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	..	..	..	..	..	..	..	..	..	..	42	6	19	27	25	1	..	11	8	4	4	..	..	37	63	..	..	..	..	..
Muscat	1928—'35	36	4	26	31	1	..	..	26	17	..	110	7	33	43	6	1	3	3	3	1	45	..	13	78	5	..	..	..	3	..
Gwador	1928—'35	355	4	1	11	33	24	24	6	1	..	87	9	32	20	..	10	7	5	11	6	35	4	15	48	15	4	..	8	4	2
Karachi	1926—'35	784	1	2	1	1	1	12	77	4	..	124	12	30	35	5	1	4	8	6	1	73	2	17	62	11	..	..	2	2	5
Quetta	1926—'34	139	11	13	8	4	4	9	20	29	3	47	7	9	26	8	6	9	16	16	2	21	10	7	..	26	8	16	22	11	..
Peshawar	1926—'35	433	3	23	50	11	1	2	..	9	..	338	7	4	3	3	8	18	32	23	1	114	7	3	7	5	5	18	41	14	..
Labore	1926—'35	289	12	7	14	25	11	10	10	11	..	155	12	6	6	11	11	13	19	20	..	43	5	5	9	9	6	36	20	4	3
Simla	1926—'27	55	8	1	4	9	11	10	27	29	..	19	3	..	1	32	11	19	6	26	..	6	33	17	..	..	..	50	..	..	..
Ahmedabad	1928—'35	394	..	..	1	3	8	40	43	3	..	62	3	14	22	4	1	29	19	6	3	17	4	10	60	10	1	1	1	4	8
Ajmer	1928—'34	425	5	11	10	5	5	24	35	6	..	86	4	27	26	11	3	10	9	5	7	76	2	28	52	8	1	5	1	1	3
Agra	1926—'35	584	11	9	24	11	4	6	17	18	..	129	3	15	32	11	3	4	13	11	7	141	4	16	35	11	4	5	18	5	1
Allahabad	1931—'35	406	3	12	35	9	4	5	19	13	..	37	11	7	18	11	1	11	12	21	9	40	5	26	31	1	2	5	8	6	15
Patna	1929—'35	519	1	4	52	19	4	4	11	5	..	86	1	13	32	15	11	2	17	6	3	186	3	23	50	11	1	2	..	2	9
Tezpur	1929—'35	185	1	6	25	7	11	25	24	1	..	57	1	4	30	9	4	21	18	4	9	47	..	19	31	12	5	4	16	4	8
Calcutta	1926—'35	645	2	4	19	18	24	19	8	4	2	66	11	..	11	10	11	17	11	6	23	79	3	22	47	18	..	..	..	..	10
Dacca	1928—'35	463	1	1	6	43	30	17	1	1	..	32	..	15	14	18	11	19	20	2	..	39	..	36	31	7	1	8	11	5	..
Chittagong	1929—'35	258	..	..	..	13	66	17	2	1	..	12	..	7	40	3	13	20	17	..	..	26	..	28	48	..	5	6	13	..	..
Akyab	1926—'35	312	2	..	2	16	35	31	9	4	1	49	3	5	17	15	16	30	11	..	2	33	3	13	43	16	10	3	4	9	..
Mandalay	1929—'35	402	1	1	2	4	45	41	5	1	..	158	3	16	21	12	7	20	13	7	1	125	4	22	50	9	3	..	3	4	4
Rangoon	1929—'35	270	..	..	1	2	18	51	28	1	..	27	..	2	..	13	..	28	52	..	5	4	..	..	25	..	13	13	25	25	..
Jaipur	1926—'35	437	7	13	18	7	4	12	27	12	..	128	9	17	26	6	3	9	15	12	4	48	6	13	29	17	3	11	8	6	7
Jubbulpore	1929—'35	524	7	5	5	2	1	7	53	21	..	94	10	14	30	10	4	12	12	4	5	81	..	10	73	10	2	1	1	3	..
Sambalpur	1930—'35	318	3	8	7	3	3	20	39	19	..	11	10	17	43	..	3	3	17	7	..	21	5	38	41	3	3	3	2	7	..
Bombay	1926—'35	787	..	..	..	..	2	41	55	..	..	67	1	9	16	6	6	32	23	7	..	30	13	33	30	4	1	..	16	2	..
Poona	1926—'35	776	..	..	..	..	..	15	82	2	..	130	8	19	21	7	4	11	9	18	2	60	2	16	68	12	1	..	..	..	1
Hyderabad	1930—'35	236	1	1	..	..	..	6	68	21	2	26	3	2	12	..	..	12	38	32	..	44	2	28	50	..	..	11	7	1	..
Waltair	1929—'35	194	1	1	..	..	5	19	61	12	..	123	5	6	5	..	..	1	42	31	8	7	19	64	13	..	..	..	..	4	..
Mangalore	1928—'35	415	..	.	..	..	..	5	70	24	..	51	5	6	11	16	4	6	23	17	14	20	..	20	69	13	..	..	..	..	..
Bangalore	1926—'35	700	..	1	..	..	..	14	79	6	..	16	..	1	3	29	..	24	26	17	..	28	1	23	38	21	4	19	2	..	..
Madras	1926—'35	382	1	1	1	1	1	5	71	19	..	218	1	6	8	2	2	10	52	12	4	236	..	16	76	4	..	1	3	..	..
Port Blair	1926—'35	685	..	..	..	1	10	66	23	..	..	82	7	11	30	16	4	9	11	9	3	89	1	31	52	5	6	..	3	..	2
Kodaikonal	1926—'35	524	2	..	1	1	..	2	66	29	..	112	3	6	20	7	..	13	29	15	6	71	4	12	51	26	3	..	3	1	1
Trivandrum	1926—'35	363	2	..	1	..	..	1	35	61	..	82	9	5	1	1	..	7	25	51	..	49	7	9	39	17	..	3	2	23	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

AUGUST.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	3	..	..	..	25	..	..	25	50	..	40	11	29	6	8	3	31	9	2	..	9	..	8	27	25	21	13	6	..	..
Muscat	1928—'34	20	..	19	25	2	8	2	26	17	2	90	11	37	19	7	..	7	12	8	..	45	1	15	76	8	..	..	..	..	..
Gwadar	1928—'35	294	..	2	12	30	28	21	5	1	1	35	4	30	38	2	2	5	5	15	..	39	2	12	65	12	..	2	3	3	..
Karachi	1926—'35	641	1	1	..	..	..	9	84	4	..	117	5	38	38	5	1	..	7	4	1	67	8	24	42	17	..	..	..	..	8
Quetta	1926—'34	83	6	14	10	11	14	14	10	21	..	58	1	9	17	11	19	11	6	25	..	22	..	4	11	26	19	21	14	5	..
Peshawar	1926—'35	469	10	8	5	8	11	21	17	19	..	391	8	3	2	4	3	25	31	25	..	111	2	..	12	3	8	23	40	13	..
Lahore	1926—'35	243	11	7	14	27	9	10	13	9	..	158	12	5	8	13	19	15	12	18	..	76	5	4	4	7	14	39	12	15	..
Simla	1926—'27	24	9	..	11	23	6	5	3	21	22	5	30	30	20	10	10	..	..	..	..	5	..	..	..	..	40	30	10	..	20
Ahmedabad	1928—'35	330	1	1	..	..	2	31	60	6	..	47	6	14	14	4	6	28	23	1	3	19	..	25	47	3	8	6	6	..	5
Ajmer	1928—'34	396	4	8	9	5	2	25	41	4	1	67	1	25	40	12	10	..	6	5	..	72	1	19	48	21	..	4	3	3	..
Agra	1926—'35	502	7	6	31	16	4	7	15	15	..	126	5	11	29	11	6	7	18	14	2	158	2	24	35	23	9	2	1	3	3
Allahabad	1930—'35	199	4	5	29	9	9	9	23	13	..	44	7	12	21	4	7	8	11	14	16	49	3	13	46	23	1	1	2	1	9
Patna	1928—'35	402	1	5	43	19	5	6	15	7	..	118	6	13	33	13	8	9	12	5	2	255	1	20	52	20	1	1	2	..	3
Tezpur	1929—'35	153	1	4	20	6	4	31	34	..	..	59	2	10	6	20	1	29	21	2	7	53	5	19	34	6	3	6	15	1	12
Calcutta	1926—'35	535	2	5	16	23	14	23	12	4	1	72	3	15	21	2	3	9	11	5	28	143	1	19	53	10	1	1	3	2	9
Dacca	1928—'35	373	..	1	6	41	28	20	3	1	..	49	..	23	27	21	3	7	13	4	2	42	1	31	39	5	1	2	4	10	6
Chittagong	1929—'35	226	..	1	3	20	60	13	2	..	..	30	..	7	25	35	11	7	5	..	10	22	..	3	72	5	7	7	7	..	..
Akyab	1926—'35	270	1	3	5	23	31	27	8	3	..	43	6	16	21	12	6	29	6	4	3	44	3	9	51	11	2	7	16	..	..
Mandalay	1929—'35	261	2	3	5	9	43	32	4	1	1	186	2	9	24	20	8	12	14	4	7	159	4	29	57	4	..	2	..	..	3
Rangoon	1928—'35	222	..	1	1	5	18	40	32	2	..	48	..	13	7	..	1	19	29	6	27	13	..	39	44	..	17	..	..	..	..
Jaipur	1926—'35	356	5	12	23	6	4	9	31	10	..	121	6	14	29	12	6	10	14	8	1	34	2	14	32	29	..	5	8	3	8
Jubbulpóre	1928—'35	417	5	5	1	2	3	8	64	12	..	115	3	17	20	10	2	14	18	13	3	145	2	4	76	13	4	1	..	..	..
Sambalpur	1930—'35	226	2	5	5	2	4	27	44	11	..	13	..	13	22	17	..	..	15	28	5	34	1	25	68	6	..	1	..	..	..
Bombay	1926—'35	682	2	1	2	1	1	24	62	9	..	73	5	8	9	3	..	34	34	7	..	102	7	19	44	13	..	..	8	9	..
Poona	1926—'35	663	..	1	1	1	1	9	84	3	..	128	7	29	17	5	1	4	15	20	..	91	1	13	67	11	1	1	6	..	..
Hydgrabad	1930—'35	184	1	3	3	6	3	9	57	17	..	34	1	11	18	15	..	3	22	33	..	49	1	26	61	4	..	..	..	8	..
Waltair	1929—'35	206	1	2	..	2	2	29	54	11	..	89	16	11	6	1	..	3	41	21	..	54	..	13	78	6	..	..	3	1	..
Mangalore	1928—'35	324	5	1	1	..	2	..	47	43	..	79	2	8	24	8	..	4	22	20	13	63	5	8	67	15	..	..	4	..	..
Bangalore	1926—'35	581	2	1	3	1	..	11	75	6	..	20	..	3	16	15	..	13	46	4	..	54	1	16	48	23	..	6	2	1	..
Madras	1926—'35	287	1	2	3	2	9	15	50	19	..	203	3	15	18	4	5	9	29	16	..	275	..	10	73	7	1	1	2	2	..
Port Blair	1926—'35	506	..	..	..	4	4	60	31	..	..	66	2	16	37	21	7	7	7	..	3	118	..	20	63	6	3	1	1	1	3
Kodaikanal	1926—'35	364	4	1	2	6	2	7	55	22	..	90	3	13	23	2	2	12	33	10	2	92	2	6	70	19	..	..	1	..	1
Trivandrum	1926—'35	301	5	1	..	..	1	3	20	71	..	96	20	13	10	8	..	1	11	38	..	37	11	20	40	8	..	..	..	19	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

SEPTEMBER.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	6	..	13	13	25	..	..	13	37	..	13	14	14	61	10	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
Muscat	1927—'34	30	8	11	2	5	13	10	15	36	..	28	2	4	30	18	7	29	5	4	..	15	..	..	54	45	..	..	..	..	..
Gwador	1927—'35	222	..	1	3	13	18	35	29	1	..	10	8	8	17	13	46	8	..	..	..	17	5	5	33	36	17	..	..	..	5
Karachi	1926—'35	453	1	3	1	..	1	5	88	2	..	27	..	37	29	19	2	5	7	..	..	74	1	7	22	24	10	7	6	6	18
Quetta	1926—'34	36	5	8	11	14	11	13	19	19	..	22	5	..	19	27	24	16	5	4	..	..	..	..	..	..	..	..	..	..	..
Peshawar	1926—'35	224	8	7	3	5	9	31	21	14	..	202	2	2	1	2	3	23	48	19	..	83	1	..	..	2	..	15	64	14	3
Lahore	1926—'35	103	30	9	6	10	11	5	13	18	..	75	3	6	3	9	15	32	25	7	..	26	..	6	7	14	6	37	30	..	..
Simla	1926—'27	30	1	..	..	17	9	7	27	39	2	13	..	10	..	3	23	43	15	7	..	5	10	..	..	..	..	50	30	10	..
Ahmedabad	1928—'35	224	2	3	4	3	3	24	53	7	..	82	1	16	17	19	7	18	9	7	5	75	1	12	27	20	10	8	17	2	2
Ajmer	1928—'34	180	9	13	7	6	4	14	35	10	..	66	8	13	20	2	16	23	9	4	6	83	3	5	12	22	13	17	19	..	10
Agra	1926—'35	294	13	13	19	11	3	6	11	23	..	94	6	11	11	14	14	21	9	5	8	99	4	4	13	22	24	18	8	3	2
Allahabad	1930—'35	179	5	15	42	7	6	4	13	8	..	53	3	12	27	19	12	8	8	3	6	24	3	10	21	30	12	2	17	..	8
Patna	1928—'35	313	2	5	37	23	5	6	14	9	1	93	3	6	10	17	11	11	32	6	4	215	6	7	31	22	8	11	5	5	7
Tezpur	1929—'35	141	1	3	25	3	4	29	33	1	..	82	2	2	15	11	3	34	25	5	1	64	5	5	10	3	2	14	35	13	13
Calcutta	1926—'35	475	2	6	17	24	22	17	6	5	1	63	..	3	24	11	3	3	2	3	48	180	1	13	52	20	4	4	1	..	6
Dacca	1928—'35	339	..	2	7	30	33	23	3	1	2	43	..	2	13	37	10	15	7	1	16	43	3	25	11	17	2	2	14	5	20
Chittagong	1929—'35	169	3	2	8	20	50	14	2	..	1	43	..	8	21	35	7	7	8	3	11	66	1	2	54	20	2	2	13	..	6
Akyab	1926—'35	357	2	7	11	26	19	16	14	6	..	77	..	5	17	45	7	7	6	6	8	113	1	11	40	26	2	3	4	5	8
Mandalay	1929—'35	271	7	4	6	16	45	16	3	3	..	131	5	6	16	32	11	10	9	10	1	188	4	28	45	9	2	1	2	1	9
Rangoon	1928—'35	296	2	4	5	12	13	26	28	7	2	53	2	6	5	9	15	18	16	2	27	30	2	12	45	9	4	4	6	2	16
Jaipur	1926—'35	208	13	16	18	5	4	4	17	24	..	111	18	7	10	3	4	15	21	10	11	40	13	14	15	23	5	12	7	8	3
Jubbulpore	1928—'35	321	13	10	12	5	7	6	26	21	..	122	7	9	33	11	5	9	14	11	..	154	1	3	61	18	6	1	7	2	1
Sambalpur	1930—'35	222	6	11	16	6	7	23	19	11	..	17	8	7	41	7	..	20	12	5	..	73	..	11	63	23	1	..	..	1	1
Bombay	1926—'35	664	7	4	3	2	4	21	41	18	..	94	10	12	15	12	3	20	14	13	2	59	8	21	30	14	9	8	8	2	..
Poona	1926—'35	550	3	5	7	4	4	12	53	13	1	174	8	20	24	11	7	9	8	12	3	154	2	19	54	21	1	1	2	..	..
Hyderabad	1929—'35	234	6	6	6	5	2	6	37	30	..	69	18	25	16	3	..	6	9	23	..	86	1	27	61	9	..	..	1	1	2
Waltair	1928—'35	176	6	6	5	3	7	21	44	7	..	68	8	13	14	11	10	7	19	15	3	78	..	5	82	11	..	..	2	..	..
Mangalore	1928—'35	328	4	1	3	1	4	13	29	40	3	86	10	5	43	18	..	..	12	12	..	95	..	26	61	9	..	1	2	..	1
Bangalore	1926—'35	513	1	1	4	1	1	14	63	14	..	39	16	16	21	2	5	13	11	16	..	83	6	21	31	28	1	8	4	2	..
Madras	1926—'35	296	9	3	5	7	3	18	32	22	..	138	6	8	18	11	4	9	24	17	3	291	1	9	73	14	..	..	1	1	1
Port Blair	1926—'35	404	..	..	2	5	4	43	38	8	..	89	10	15	23	21	4	9	8	8	1	100	..	17	66	9	..	2	1	1	4
Kodaikanal	1926—'35	309	7	5	6	11	7	5	41	19	..	62	4	10	26	8	1	12	21	11	6	108	..	11	76	9	1	..	1	1	1
Trivandrum	1926—'35	246	7	3	2	..	1	3	13	68	..	86	23	8	10	4	..	2	11	43	..	104	7	17	49	9	1	3	5	8	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

OCTOBER.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1928—'35	15	31	33	2	..	..	6	10	18	..	20	..	..	..	6	27	11	33	7	16	40	..	..	..	..	4	33	59	4	..
Muscat	1927—'34	42	2	10	23	8	11	17	19	10	..	33	8	3	1	1	15	49	13	8	2	28	..	..	..	..	5	67	27	..	..
Gwador	1927—'35	127	..	2	8	11	15	23	37	4	..	26	..	..	15	15	3	58	8	..	..	22	..	..	10	10	..	36	43	1	..
Karachi	1926—'35	169	3	13	2	1	4	12	60	5	1	49	5	5	12	5	17	40	9	1	7	50	..	2	5	2	..	45	19	17	9
Quetta	1926—'34	44	..	4	..	4	3	23	50	15	2	25	2	10	6	2	3	42	18	17	..	27	..	..	..	3	1	50	41	6	..
Peshawar	1926—'35	176	3	1	6	6	12	35	28	9	1	197	2	3	1	1	8	29	40	14	1	173	1	1	3	2	4	25	57	6	1
Lahore	1926—'35	36	6	5	6	3	22	41	8	9	..	51	..	1	2	6	25	33	20	14	..	28	..	..	..	..	13	23	52	12	..
Simla	1926—'27	20	2	..	4	23	27	10	5	16	12	17	4	..	2	35	32	13	..	4	10	5	30	..	..	..	..	10	30	30	..
Ahmedabad	1928—'35	113	3	17	10	7	7	22	25	9	..	71	1	3	16	7	12	28	29	4	..	43	..	2	2	8	7	57	25	..	..
Ajmer	1928—'34	140	6	11	8	7	7	10	30	21	2	46	1	..	..	9	6	45	34	5	..	13	..	..	..	..	..	64	36	..	..
Agra	1926—'35	137	4	7	19	5	1	9	29	28	..	81	4	2	2	10	4	17	36	25	..	40	..	..	..	1	2	33	50	8	6
Allahabad	1930—'35	87	2	9	42	4	9	8	13	13	..	29	..	5	1	5	9	34	19	10	17	14	..	..	..	8	..	34	41	..	17
Patna	1928—'35	227	3	9	26	13	4	4	23	18	..	95	5	3	4	5	14	35	26	7	1	104	..	..	..	..	3	42	47	6	2
Tezpur	1929—'35	169	..	7	24	3	4	33	29	..	..	71	2	..	1	2	2	40	47	3	2	19	..	3	..	..	2	14	68	3	10
Calcutta	1926—'35	440	12	10	10	11	10	17	11	13	5	63	1	1	3	1	14	15	27	..	25	112	4	4	11	13	13	26	13	4	12
Dacca	1928—'35	310	11	6	5	10	17	22	10	12	8	65	..	..	8	9	8	29	33	9	3	30	2	3	1	2	2	59	26	6	..
Chittagong	1929—'35	164	15	14	5	6	25	21	6	6	..	22	..	..	10	3	9	40	26	..	10	37	1	8	3	1	1	18	39	7	20
Akyab	1926—'35	333	10	19	10	18	12	11	11	9	..	62	7	9	24	22	7	12	11	5	5	76	1	6	20	17	6	13	20	11	7
Mandalay	1929—'35	276	7	4	9	12	23	24	8	12	5	112	2	3	7	8	19	17	32	10	2	151	5	12	7	3	15	18	25	9	7
Rangoon	1928—'35	373	3	13	24	25	12	6	8	5	4	49	2	6	22	35	5	4	2	..	23	49	1	9	23	14	3	..	8	1	40
Jaipur	1926—'35	141	12	9	14	3	3	15	14	24	5	96	3	4	5	12	4	16	34	19	2	24	..	..	..	..	2	45	46	7	..
Jubbulpore	1928—'35	190	18	18	17	8	9	8	11	11	..	109	7	7	13	9	7	25	21	11	..	100	1	..	11	4	15	27	37	2	3
Sambalpur	1930—'35	203	6	24	18	10	5	18	10	8	..	36	1	5	16	..	8	53	15	3	..	52	..	..	5	28	11	41	14	1	..
Bombay	1926—'35	460	15	8	15	13	7	10	12	19	..	131	5	16	15	21	12	12	8	9	2	176	6	12	17	24	11	16	11	2	1
Poona	1926—'35	431	5	16	30	19	4	8	8	10	1	187	6	14	19	18	11	11	3	9	8	174	2	7	13	17	17	29	11	3	1
Hyderabad	1929—'35	259	9	17	29	17	4	8	6	9	..	57	12	21	21	21	2	6	12	5	..	76	5	10	33	19	18	0	1	..	5
Waltair	1928—'35	195	8	20	28	7	9	15	9	4	..	62	11	16	25	16	4	11	11	4	2	117	1	14	31	28	8	15	3	1	1
Mangalore	1928—'35	366	9	9	6	8	10	10	21	26	..	133	..	17	39	22	2	6	12	1	..	150	..	10	47	25	12	4	1	1	..
Bangalore	1926—'35	559	5	23	21	5	1	11	25	8	..	38	5	10	20	24	11	7	8	15	..	99	3	14	27	44	5	5	3	..	..
Madras	1926—'35	465	11	28	24	6	4	7	10	10	..	121	3	12	35	15	3	11	10	11	2	240	1	7	50	31	4	3	1	1	2
Port Blair	1926—'35	550	1	7	27	14	7	19	17	4	1	107	3	17	32	15	9	6	4	5	8	134	1	13	58	19	4	1	1	..	3
Kodaikanal	1926—'35	407	18	16	12	9	5	9	14	16	1	49	5	13	42	10	4	10	3	8	2	86	1	9	63	24	2	..	..	1	..
Trivandrum	1926—'35	286	8	4	6	2	3	6	31	38	..	85	19	23	13	8	1	4	10	21	..	87	1	21	46	20	7	..	4	..	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India.

NOVEMBER.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1027—'35	73	19	2	..	..	6	24	25	23	..	48	..	..	..	..	2	36	61	..	..	124	..	..	..	..	..	27	61	12	..
Muscat	1927—'31	63	18	4	8	2	10	13	22	25	..	17	..	..	..	..	1	67	22	8	..	107	..	..	..	..	..	47	52	1	..
Gwador	1927—'35	36	..	..	4	..	12	46	38	..	..	35	..	..	..	2	5	43	50	..	..	116	..	..	1	..	1	26	57	9	4
Karachi	1926—'35	48	..	1	2	1	3	30	50	14	..	59	1	5	..	..	4	55	31	4	..	170	..	..	..	..	..	18	65	9	7
Quetta	1926—'34	65	..	2	..	..	5	27	58	9	..	48	..	..	..	..	3	34	45	19	..	80	1	..	..	..	..	34	45	20	..
Peshawar	1926—'35	122	..	7	2	6	30	29	16	9	1	225	1	1	2	2	7	32	50	5	..	461	..	..	..	..	1	17	65	16	..
Lahore	1926—'35	27	..	..	2	7	13	50	28	..	..	62	..	..	..	..	7	30	60	4	..	132	1	..	..	..	2	18	69	10	..
Simla	1926—'27	9	..	..	11	72	6	11	..	..	..	16	2	7	..	..	9	14	51	12	4	20	..	..	..	..	..	30	61	9	..
Ahmedabad	1928—'35	40	4	20	5	..	20	26	19	6	..	29	..	..	..	2	4	71	23	..	..	80	..	..	..	..	5	44	43	7	..
Ajmer	1928—'33	21	..	..	..	4	8	43	29	16	..	31	..	..	..	..	..	49	50	1	..	101	..	..	..	..	..	28	55	17	..
Agra	1926—'35	43	9	11	1	4	3	25	33	16	..	37	..	6	6	..	1	35	46	6	..	147	..	..	..	..	..	22	70	8	..
Allahabad	1930—'35	31	6	15	15	4	2	4	38	16	..	20	..	..	..	..	..	55	39	5	..	27	..	..	..	..	..	70	30	..	..
Patna	1928—'35	69	1	9	24	10	2	4	19	25	4	34	..	8	5	..	..	24	57	5	..	88	..	..	..	..	..	36	60	4	..
Tezpur	1928—'35	124	1	7	29	15	4	27	15	2	2	63	3	1	1	3	4	12	60	14	2	30	2	..	..	..	..	4	63	31	..
Calcutta	1926—'35	183	25	19	5	3	7	11	12	18	1	38	12	1	..	2	6	35	22	7	16	138	..	..	1	..	5	68	24	1	2
Dacca	1928—'35	199	12	11	4	4	4	12	18	21	17	49	2	2	..	..	3	41	18	4	..	41	1	..	..	..	..	33	55	12	..
Chittagong	1928—'35	110	17	16	6	8	21	13	13	7	..	25	2	..	2	..	12	42	35	6	..	71	..	1	..	..	3	32	51	7	6
Akyab	1926—'35	195	11	19	5	11	12	18	14	10	..	38	6	6	2	9	19	23	22	14	..	117	..	..	..	1	9	35	45	10	1
Mandalay	1928—'35	205	9	2	2	5	24	36	15	7	1	71	..	2	1	12	12	34	33	4	1	82	..	..	..	1	1	29	63	7	..
Rangoon	1928—'35	252	6	12	32	20	7	6	3	6	8	36	5	9	7	35	5	15	5	7	12	52	..	4	5	13	16	26	19	12	5
Jaipur	1926—'35	24	8	11	4	..	9	38	21	10	..	62	7	2	..	..	2	29	45	13	..	104	2	..	..	..	2	24	56	16	..
Jubbulpore	1928—'35	69	15	14	6	7	4	8	31	15	..	48	7	..	1	..	4	40	40	8	..	96	..	..	..	..	3	44	52	2	..
Sambalpur	1930—'35	96	11	14	9	8	10	19	15	15	..	11	..	..	..	..	..	55	30	15	..	71	..	..	..	4	2	63	30	..	..
Bombay	1926—'35	174	6	23	16	7	22	17	4	6	..	69	2	2	4	22	22	29	19	..	2	215	2	1	3	16	14	45	11	3	5
Poona	1926—'35	166	8	11	28	18	12	15	6	2	1	65	1	10	10	18	24	23	11	4	..	173	1	..	..	3	18	51	24	3	..
Hyderabad	1929—'35	124	6	20	22	20	12	2	12	6	..	23	9	18	13	17	17	17	9	..	..	91	3	1	1	9	40	39	5	..	..
Waltair	1928—'35	106	9	43	27	9	2	3	3	5	..	48	13	5	27	21	9	10	4	3	8	132	1	..	1	2	28	51	15	1	..
Mangalore	1928—'35	167	10	10	30	10	7	14	8	11	..	99	2	13	40	25	7	3	9	..	..	176	1	3	25	35	15	11	9	2	..
Bangalore	1926—'35	394	4	30	40	10	3	5	4	3	..	34	..	28	25	20	15	6	5	2	..	157	..	5	17	37	17	15	5	3	..
Madras	1926—'35	624	12	56	18	5	3	2	2	2	..	87	9	19	31	15	4	10	4	5	4	223	2	3	14	32	24	16	4	1	5
Port Blair	1926—'35	560	1	24	49	14	4	4	3	1	..	82	3	14	40	15	12	13	..	3	..	142	5	6	27	38	11	3	3	1	7
Kodaikanal	1926—'35	328	16	16	20	18	4	5	10	12	..	42	3	11	41	21	2	11	7	4	..	108	2	6	21	43	18	10	1	..	1
Trivandrum	1926—'35	298	7	16	8	8	5	18	18	21	..	101	8	28	26	16	4	12	1	4	1	88	6	12	29	41	6	1	3	2	..

APPENDIX B.

Normal percentage frequencies of direction of movement of clouds over India

DECEMBER.

Station.	Years.	No. of Obsns.	Low Clouds.								Stationary.	No. of Obsns.	Medium Clouds.								Stationary.	No. of Obsns.	High Clouds.								Stationary.
			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW			N	NE	E	SE	S	SW	W	NW	
Bahrein	1927—'35	140	23	3	1	2	3	17	29	22	..	101	..	..	..	1	..	18	63	17	1	79	..	..	..	..	..	27	63	10	..
Muscat	1927—'34	138	6	2	6	4	3	18	40	19	..	40	6	..	..	3	..	16	51	25	..	98	1	..	..	..	..	28	56	15	..
Gwador	1927—'35	92	1	1	20	17	11	22	25	4	..	45	..	..	..	5	..	34	55	6	..	142	1	..	..	..	1	11	68	15	2
Karachi	1926—'35	77	6	4	..	1	4	17	52	15	2	88	1	..	..	..	4	26	62	7	..	212	2	..	..	..	1	12	73	13	..
Quetta	1926—'34	128	3	1	..	1	7	32	42	15	..	69	3	..	..	..	2	31	46	19	..	75	1	..	..	..	..	37	51	11	..
Peshawar	1926—'35	180	7	6	11	11	29	22	8	6	..	322	1	1	5	4	9	44	32	5	..	432	1	1	..	1	3	19	66	10	..
Lahore	1926—'35	77	2	2	7	13	24	32	18	2	..	115	..	..	1	2	6	44	41	6	..	164	1	..	..	..	1	21	58	19	..
Simla	1926—'27	4	..	..	..	25	37	12	25	..	..	39	..	..	4	6	7	50	29	3	..	33	..	..	..	..	..	30	61	9	..
Ahmedabad	1928—'35	29	1	1	3	..	14	44	27	10	..	35	..	1	1	1	5	35	45	13	..	71	..	..	..	..	..	16	72	12	..
Ajmer	1928—'35	49	4	3	1	1	7	40	41	3	1	45	..	..	..	..	7	48	42	3	..	77	3	..	..	..	..	22	69	5	..
Agra	1926—'35	81	1	2	2	2	7	42	39	5	..	73	..	..	..	..	1	27	70	1	1	170	1	..	..	..	..	21	76	3	..
Allahabad	1930—'35	35	..	2	..	..	4	25	57	13	..	39	..	..	..	..	..	22	67	8	3	25	..	..	..	..	..	39	59	2	..
Patna	1928—'35	61	5	6	12	6	3	13	36	18	..	59	3	..	..	..	1	27	64	5	..	109	..	..	..	..	..	34	63	3	..
Tezpur	1928—'35	116	2	3	29	6	1	29	23	7	1	42	..	2	2	9	..	27	49	12	..	35	..	..	..	..	1	21	77	1	..
Calcutta	1926—'35	134	26	10	2	2	1	20	17	21	2	40	3	..	6	..	4	31	44	3	9	107	2	..	..	..	..	55	35	3	6
Dacca	1928—'35	136	8	3	6	1	2	22	27	27	4	45	..	..	..	..	4	37	56	3	..	28	..	..	..	..	..	29	71	..	..
Chittagong	1928—'35	58	6	19	4	7	17	24	20	3	1	53	1	..	..	..	4	37	56	2	..	85	..	1	..	2	3	21	73	1	..
Akyab	1926—'35	140	14	29	1	3	8	15	23	9	..	50	..	..	..	9	14	28	38	10	..	93	..	..	..	..	3	35	48	9	6
Mandalay	1928—'35	133	7	3	8	9	21	30	19	3	..	51	..	..	..	..	25	75	..	..	..	75	..	..	..	..	..	40	60	..	..
Rangoon	1928—'35	201	8	20	27	14	9	9	7	3	4	33	..	5	9	29	18	24	12	..	4	67	..	3	9	5	23	33	20	..	6
Jaipur	1926—'35	72	2	4	6	4	7	42	32	3	..	78	1	..	..	..	3	47	47	2	..	133	1	..	..	..	1	30	63	5	..
Jubbulpore	1928—'35	90	5	2	2	..	3	25	48	15	...	67	..	..	..	..	1	19	76	4	..	98	..	..	..	..	..	19	76	5	..
Sambalpur	1930—'35	66	6	4	2	..	..	15	50	22	..	9	..	..	..	..	..	42	50	8	..	36	..	..	..	..	..	62	36	2	..
Bombay	1926—'35	107	4	9	15	17	18	15	13	9	..	57	..	..	4	16	25	40	14	2	..	159	1	..	3	9	15	44	21	5	3
Poona	1926—'35	159	1	4	18	16	21	23	17	2	..	37	..	..	4	3	22	45	26	1	..	142	..	..	..	..	8	44	43	3	3
Hyderabad	1929—'35	111	6	17	20	32	4	6	8	8	..	15	..	6	..	22	27	9	18	19	..	72	1	..	..	5	12	63	17	2	..
Waltair	1928—'35	62	16	30	21	14	9	3	..	7	..	61	..	4	9	18	13	22	17	17	..	115	..	..	..	..	11	70	19	..	..
Mangalore	1928—'35	115	..	13	37	16	7	18	3	8	..	76	..	15	27	23	17	15	2	..	..	179	1	1	12	18	28	22	13	5	..
Bangalore	1926—'35	361	1	29	57	8	1	1	1	1	..	26	..	29	23	11	2	19	5	10	..	146	..	3	6	25	15	38	10	2	..
Madras	1926—'35	594	7	65	25	3	..	..	..	..	..	70	14	7	26	12	13	20	3	4	3	195	..	..	3	16	28	33	15	1	5
Port Blair	1926—'35	555	3	38	51	6	1	..	1	1	..	75	8	15	36	19	8	2	4	5	2	139	1	1	8	38	24	17	6	1	7
Kodaikanal	1926—'35	313	8	21	27	20	3	5	2	13	1	18	..	..	44	27	5	11	7	..	7	140	1	2	12	40	13	16	7	3	7
Trivandrum	1926—'35	257	6	28	20	10	2	12	10	12	..	79	7	33	37	9	1	6	2	4	..	152	3	6	32	30	7	8	8	5	..

MGIPC—M—XI-1-4—15-11-38—405.

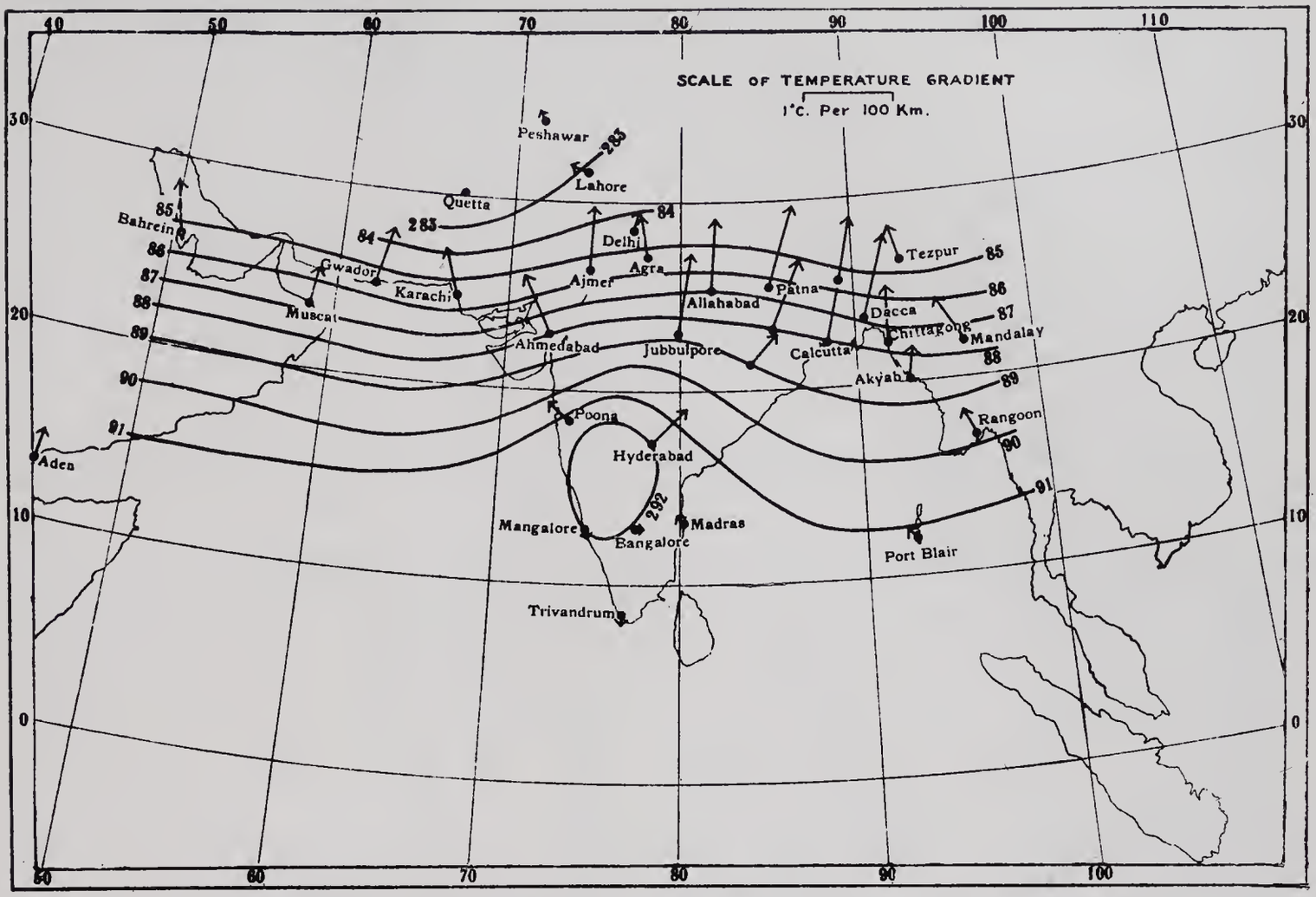


Fig. 1. Horizontal gradients of temperature at 1 to 2 km. in January computed from the normal pilot balloon winds at 1 & 2 km. Isotherms are drawn using these gradients and the mean temperatures over Agra & Poona.

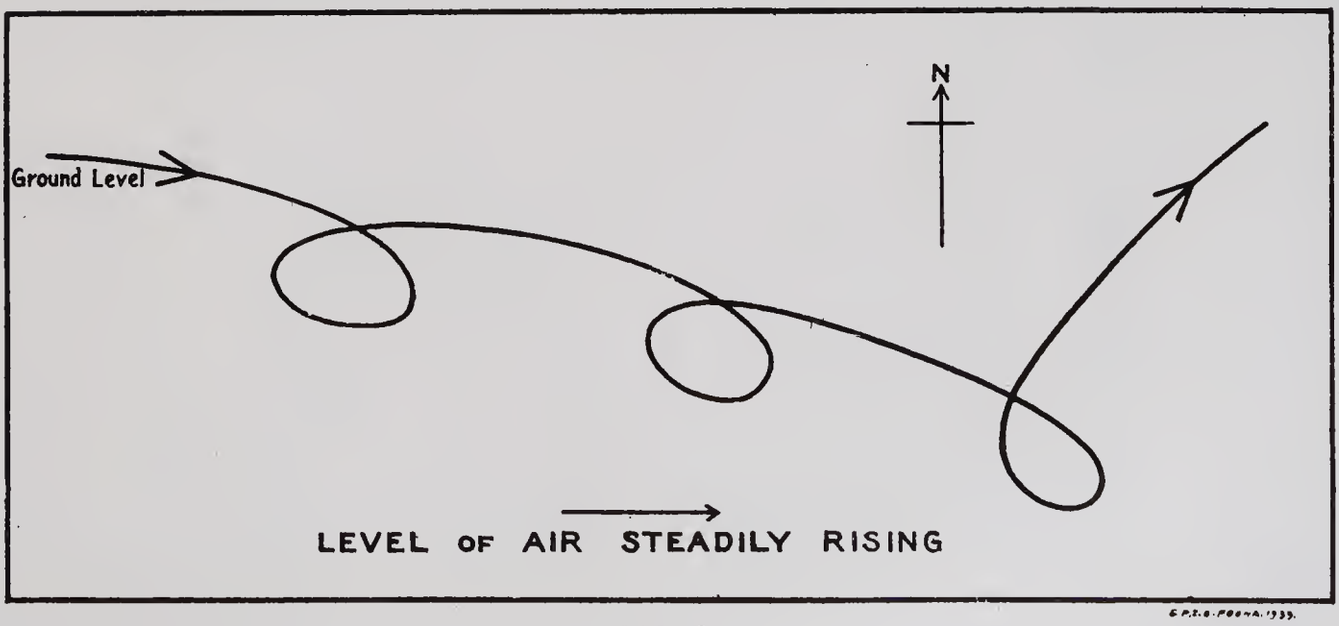


FIG. 2.

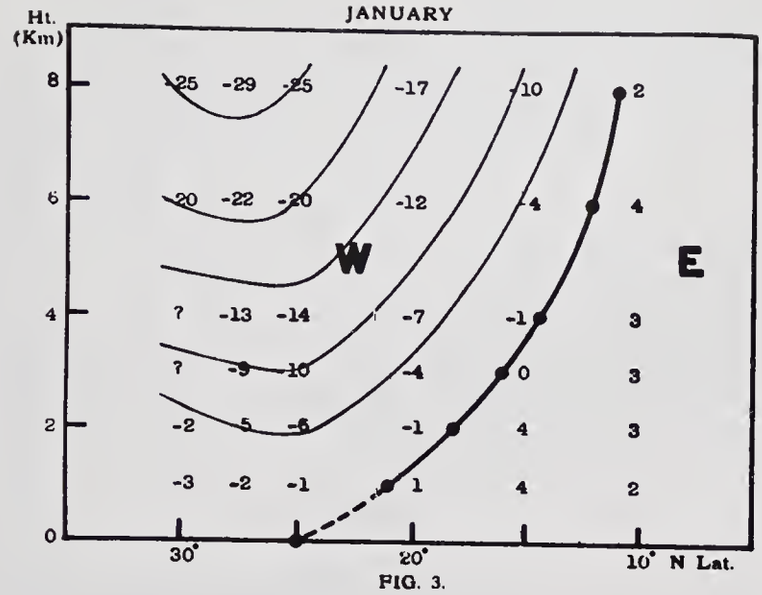


FIG. 3.

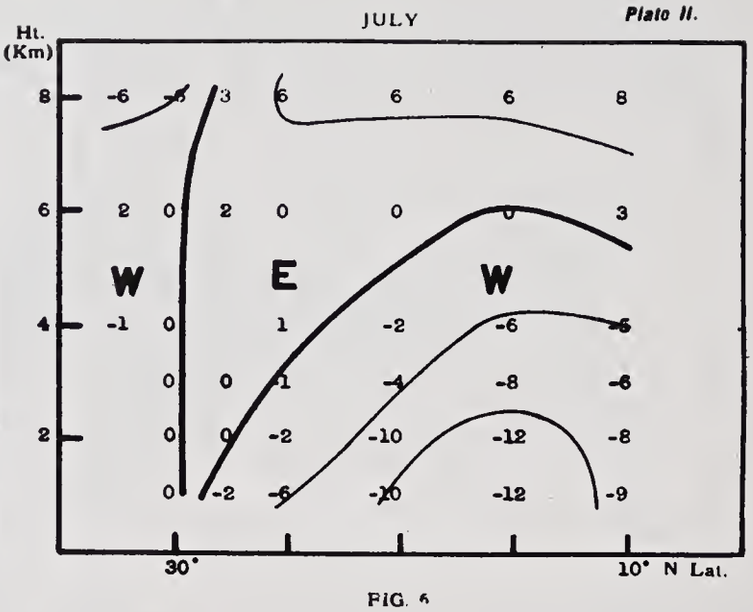


FIG. 6

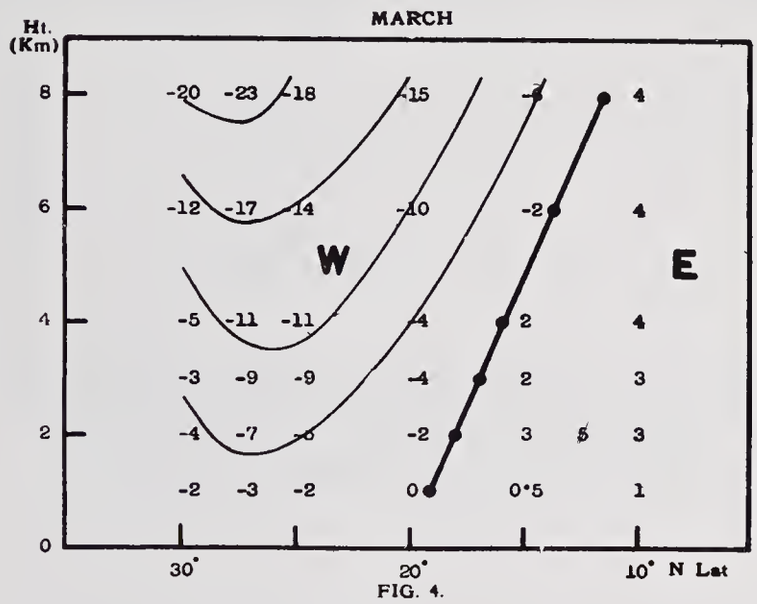


FIG. 4.

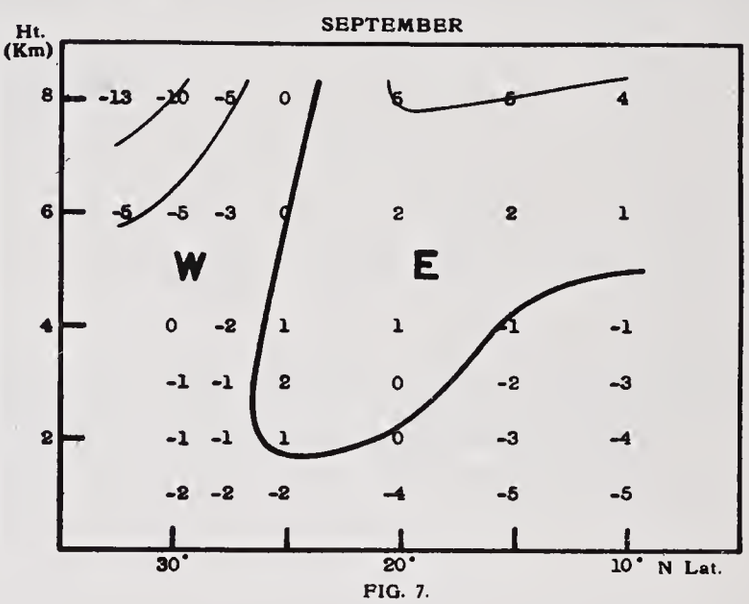


FIG. 7.

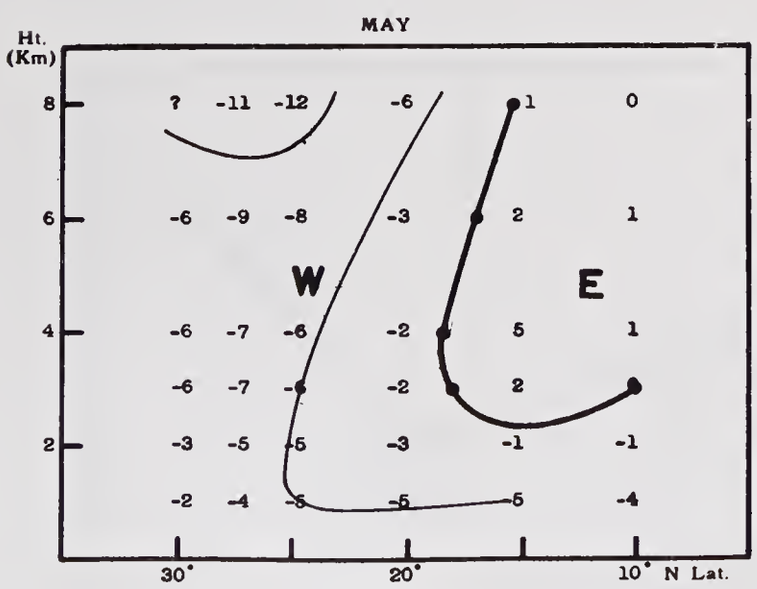


FIG. 5.

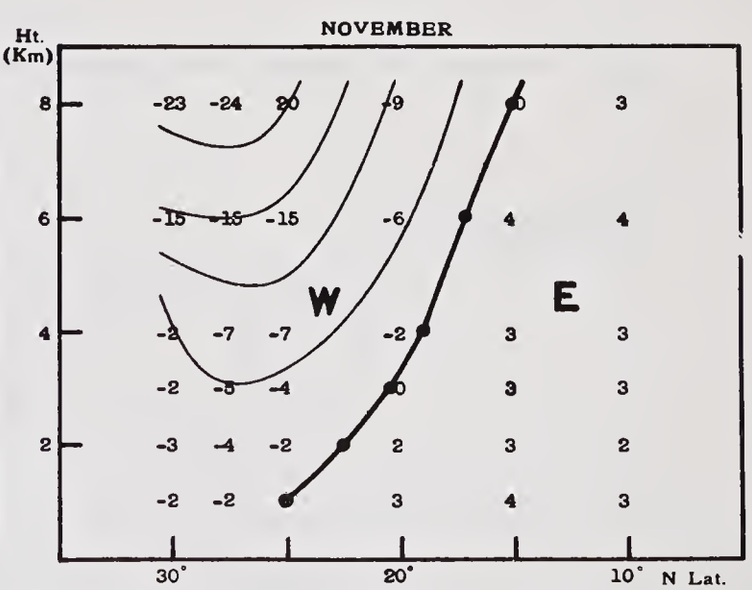
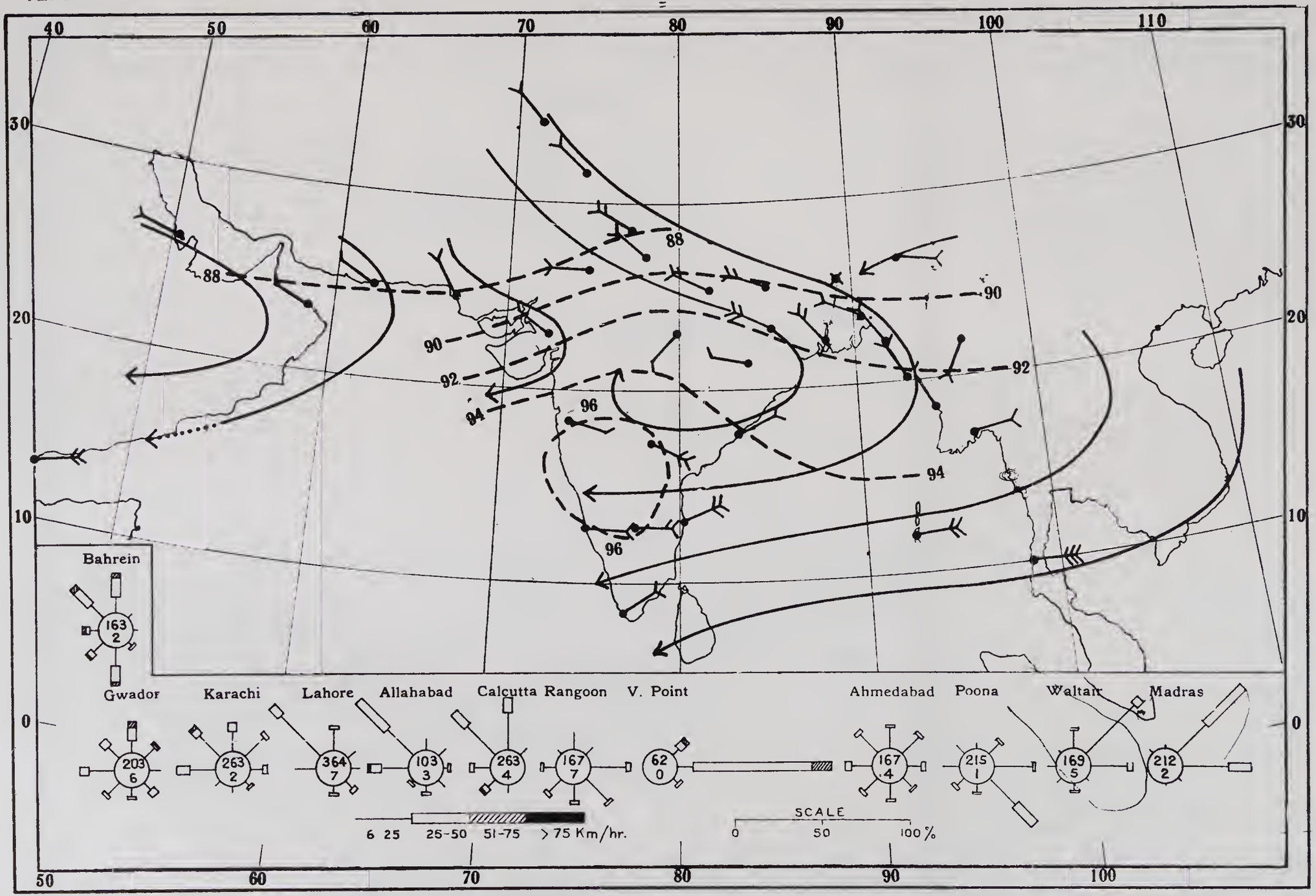


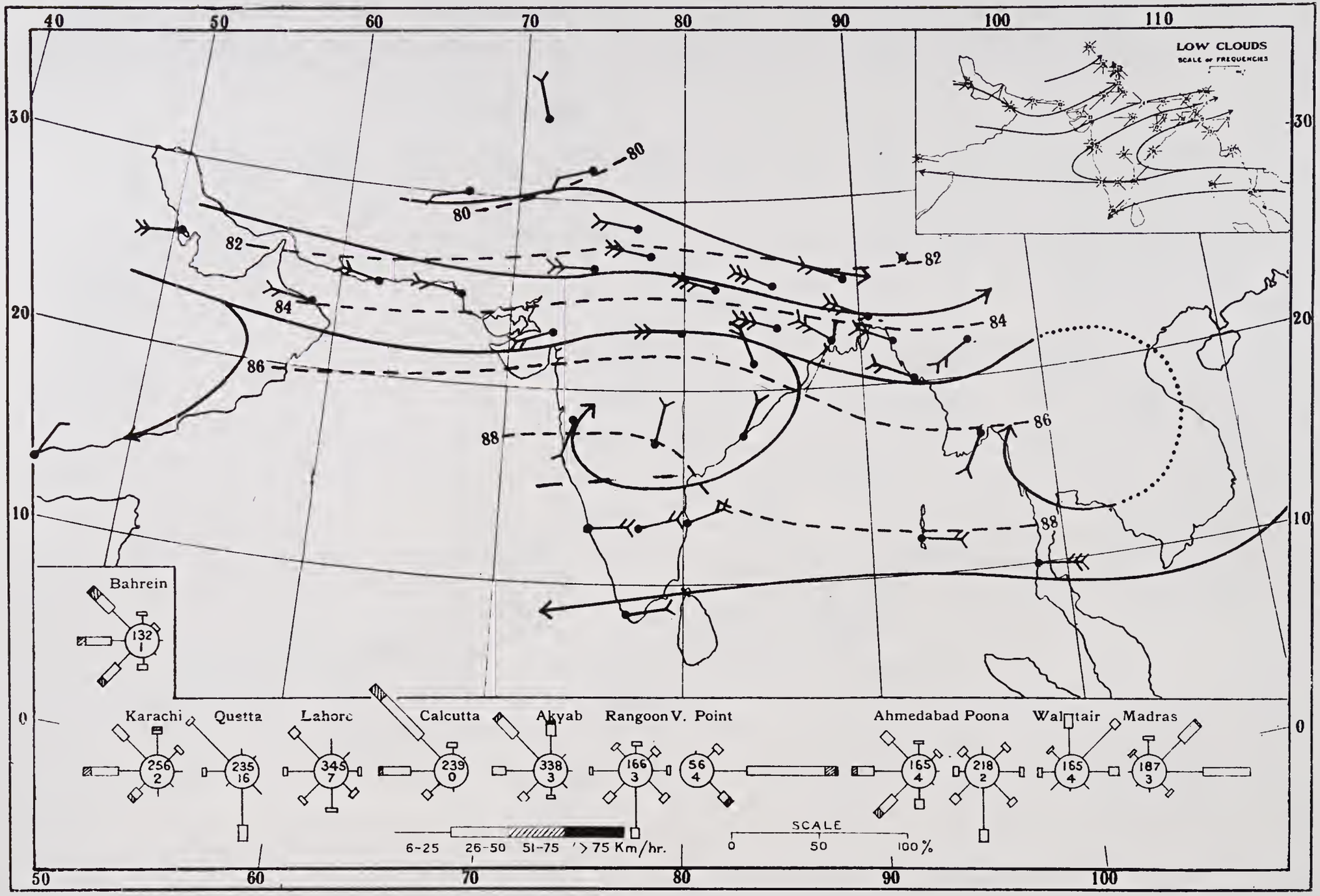
FIG. 8.

The variation of the normal west-east component of wind (metres per second) along longitude 78° E.

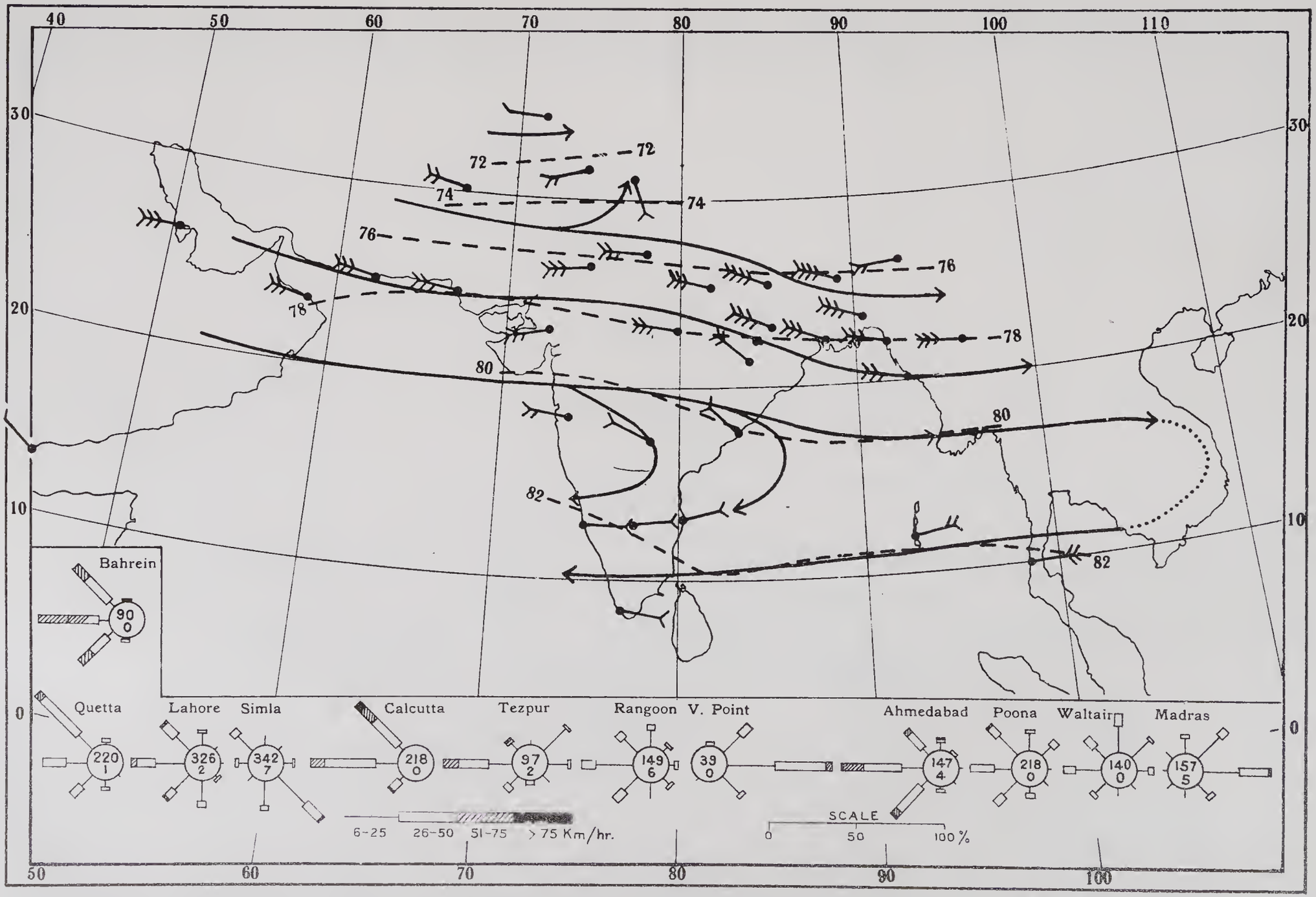
PLATE III



UPPER WINDS AND TEMPERATURES OVER INDIA —— JANUARY 1 KM.

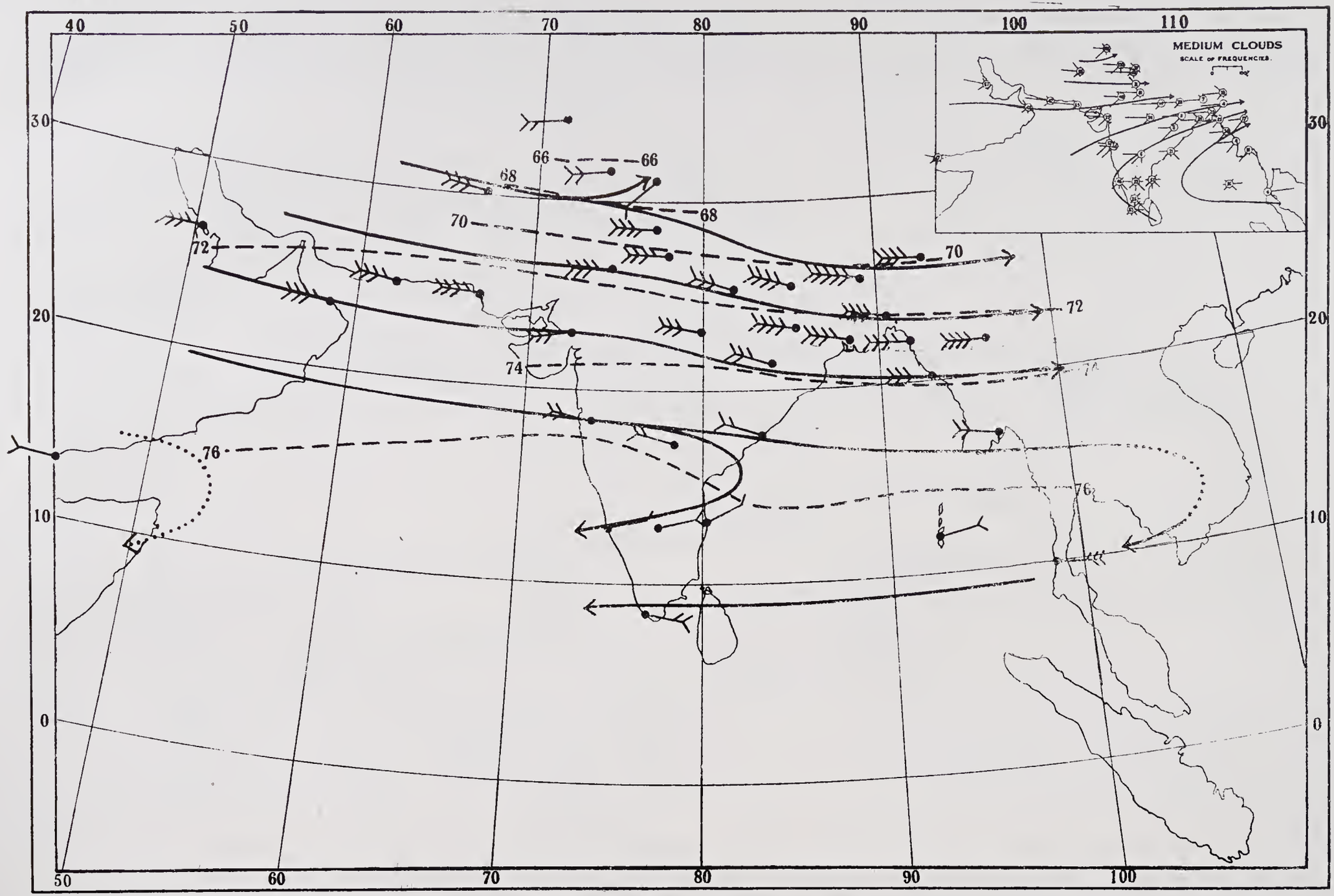


UPPER WINDS AND TEMPERATURES OVER INDIA —— JANUARY 2 KM.

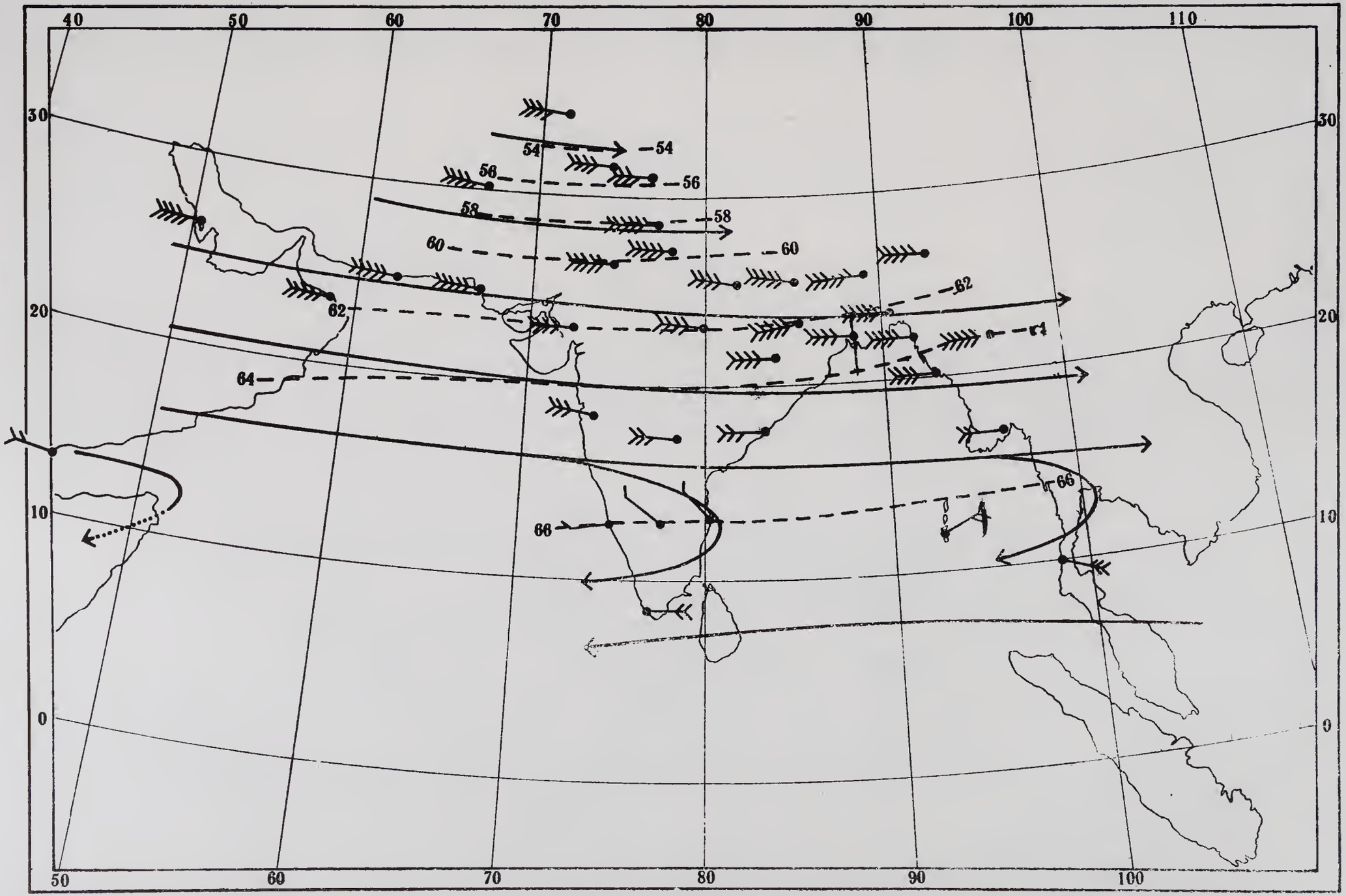


UPPER WINDS AND TEMPERATURES OVER INDIA —— JANUARY 3 KM.

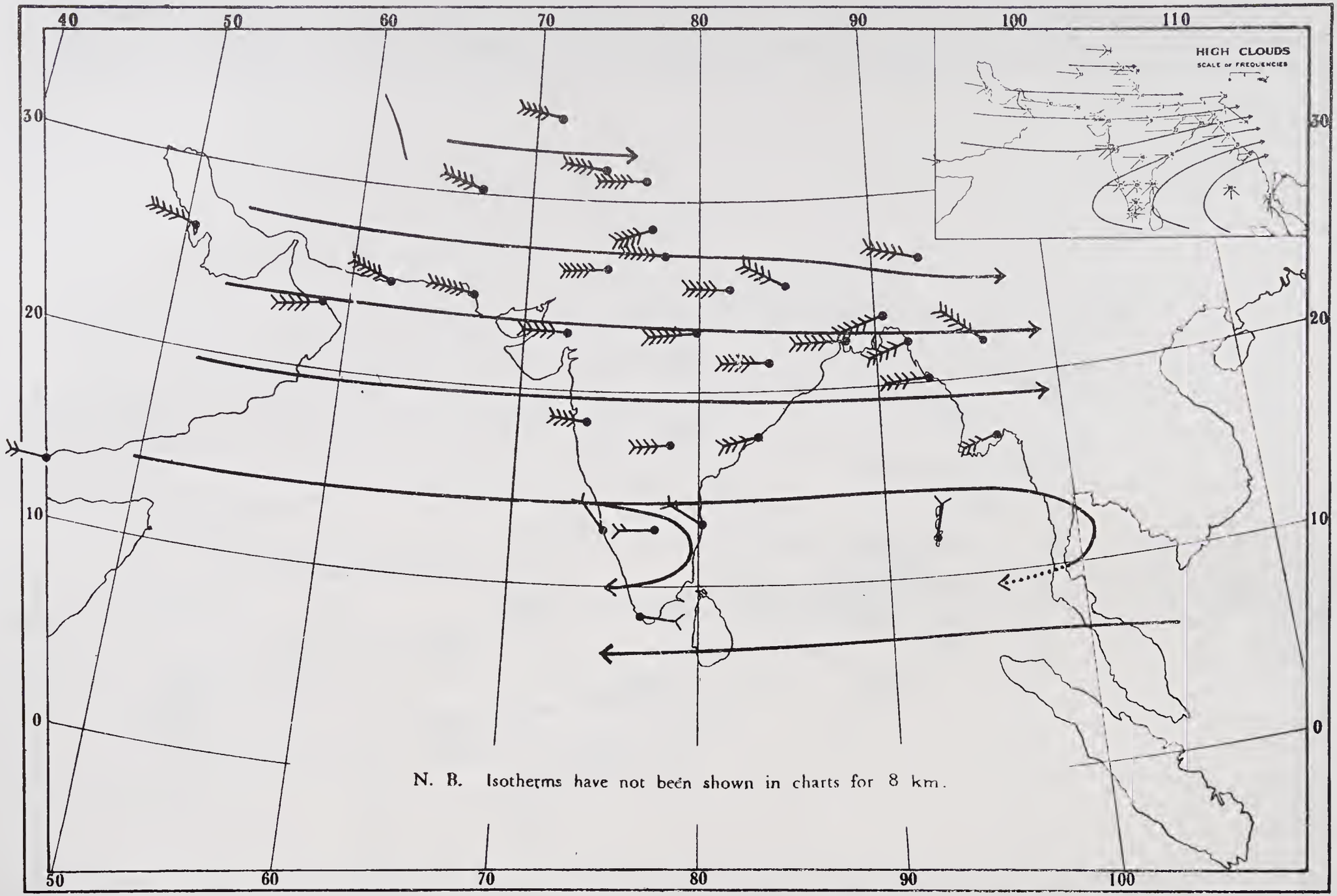
PLATE VI



UPPER WINDS AND TEMPERATURES OVER INDIA —— JANUARY 4 KM.

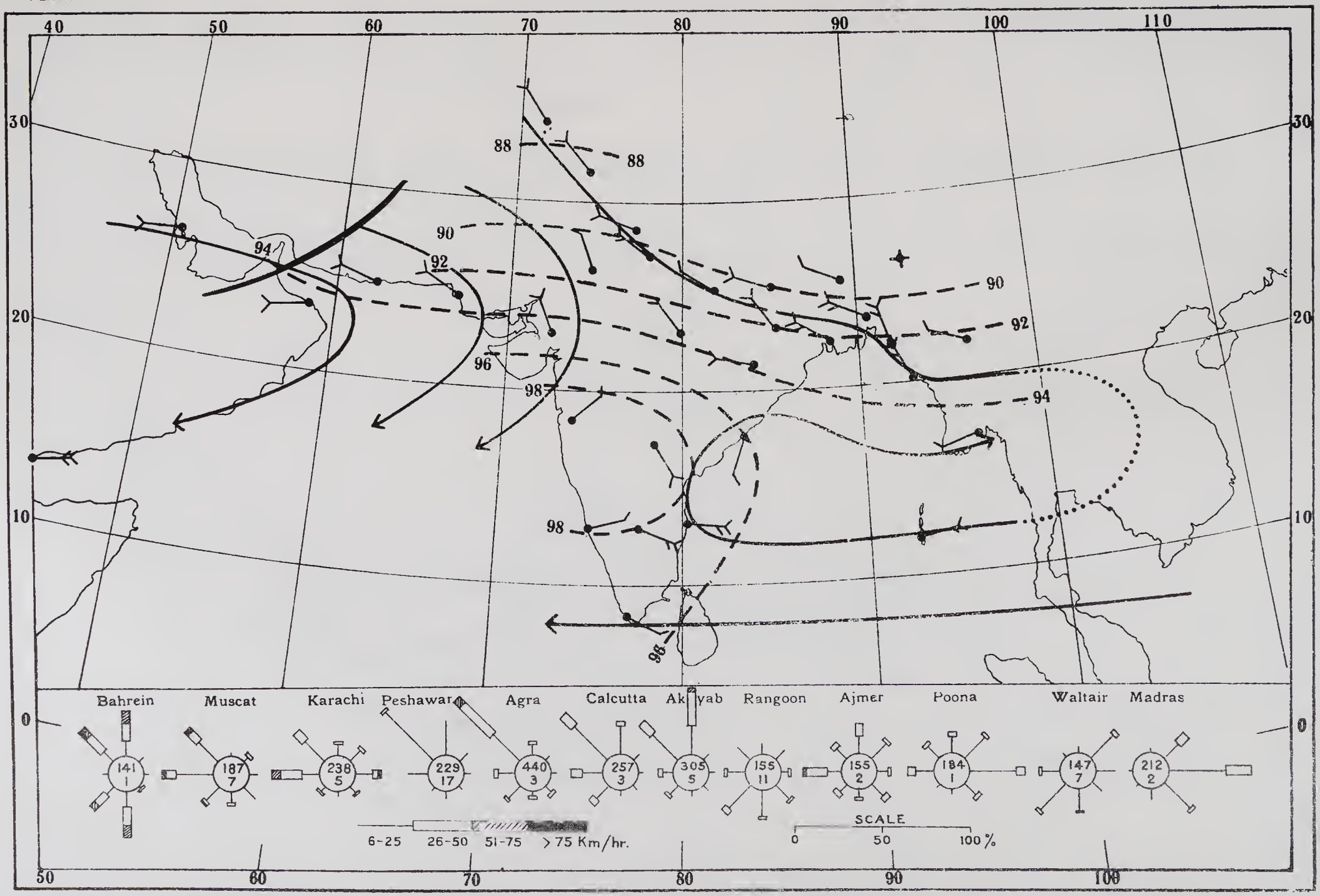


UPPER WINDS AND TEMPERATURES OVER INDIA —— JANUARY 6 KM.

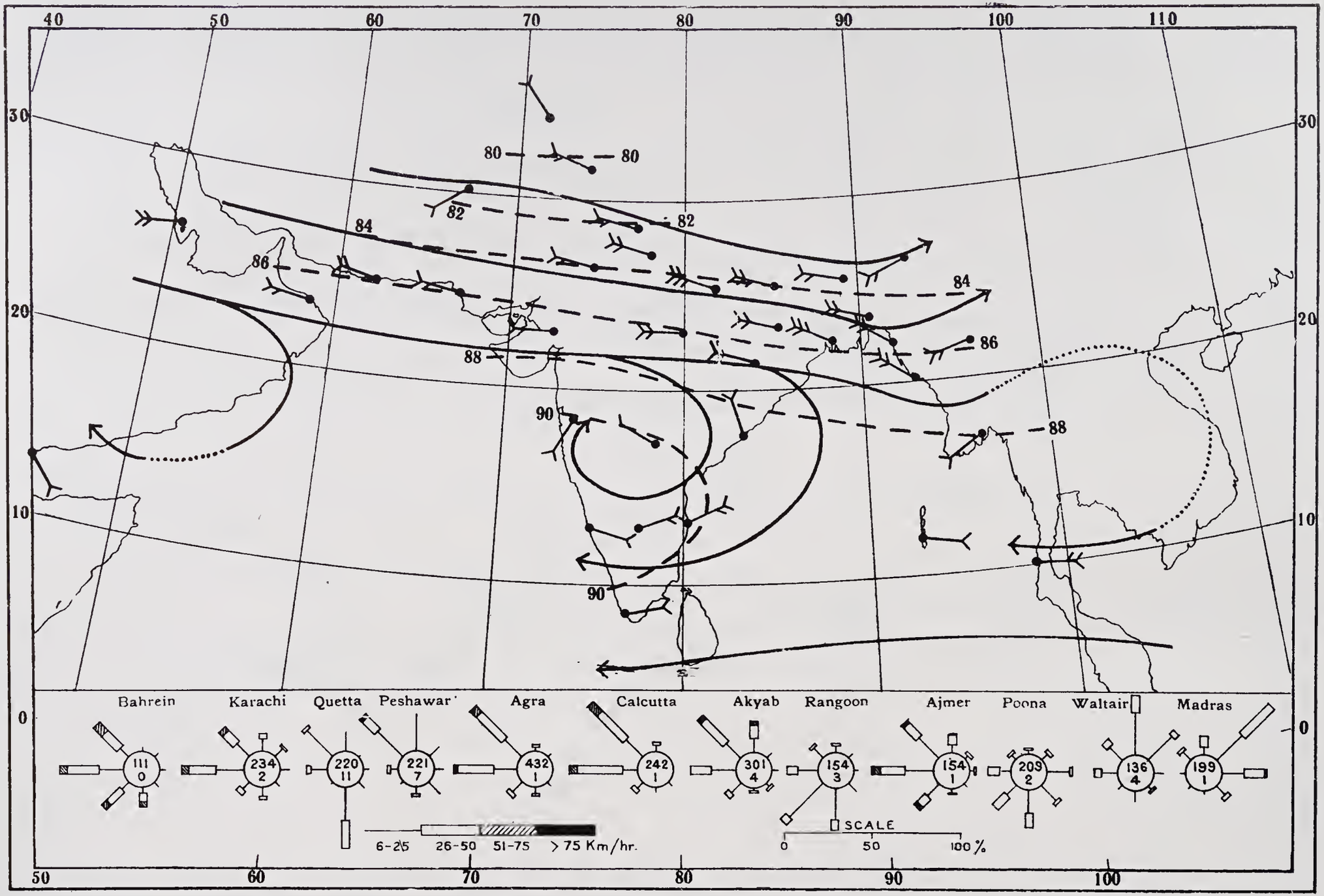


UPPER WINDS AND TEMPERATURES OVER INDIA —— JANUARY 8 KM.

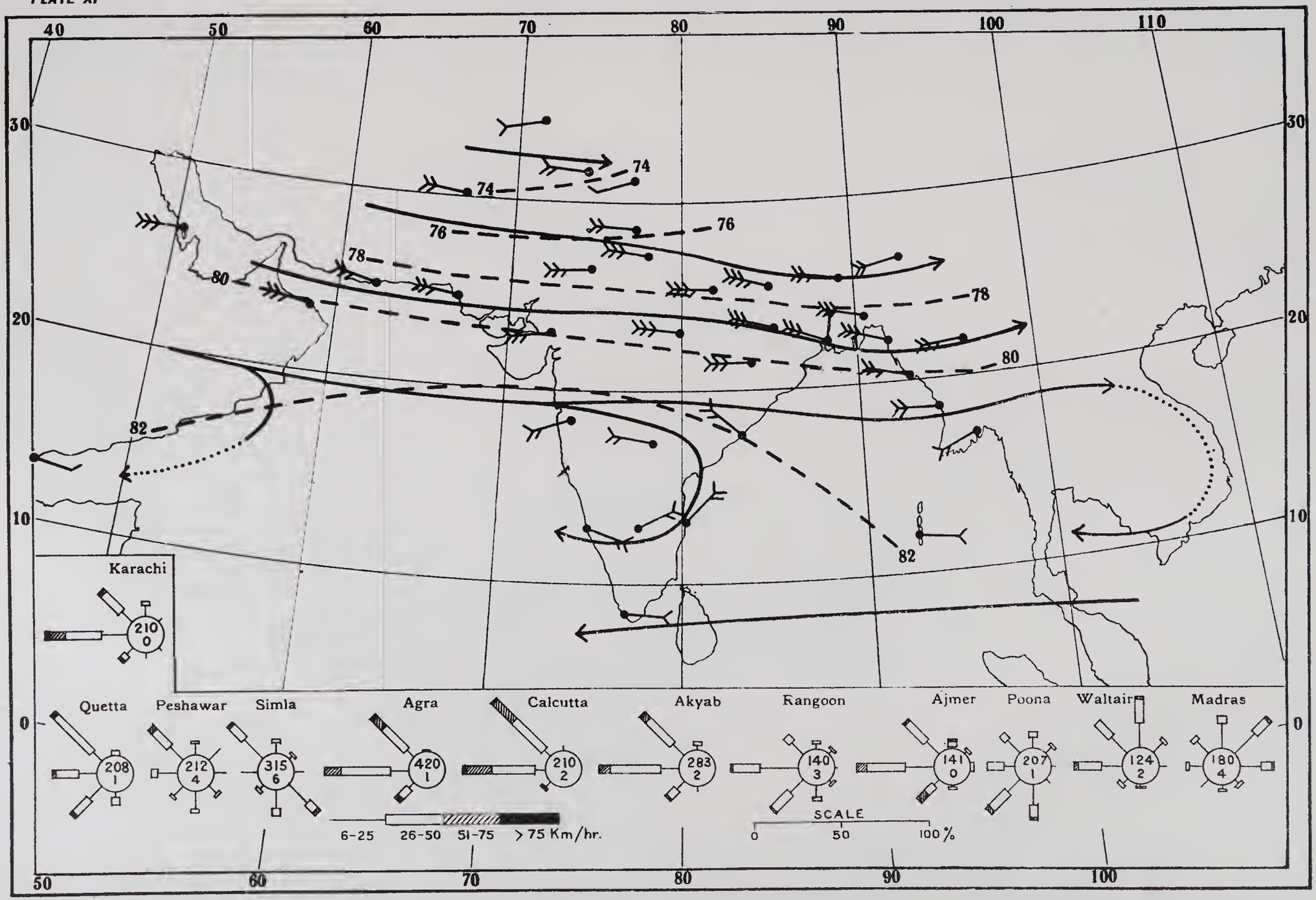
PLATE IX



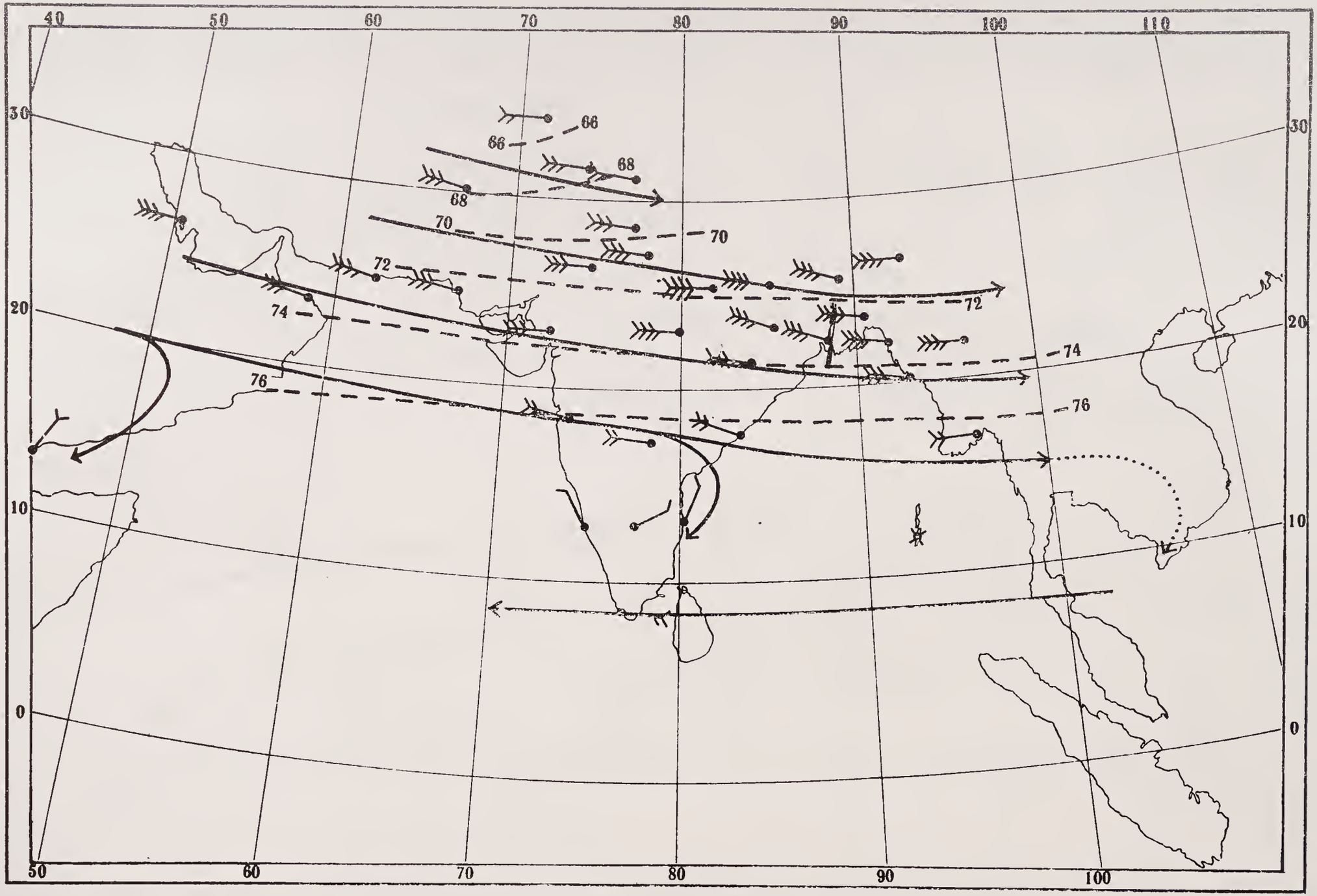
UPPER WINDS AND TEMPERATURES OVER INDIA —— FEBRUARY 1 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— FEBRUARY 2 KM.

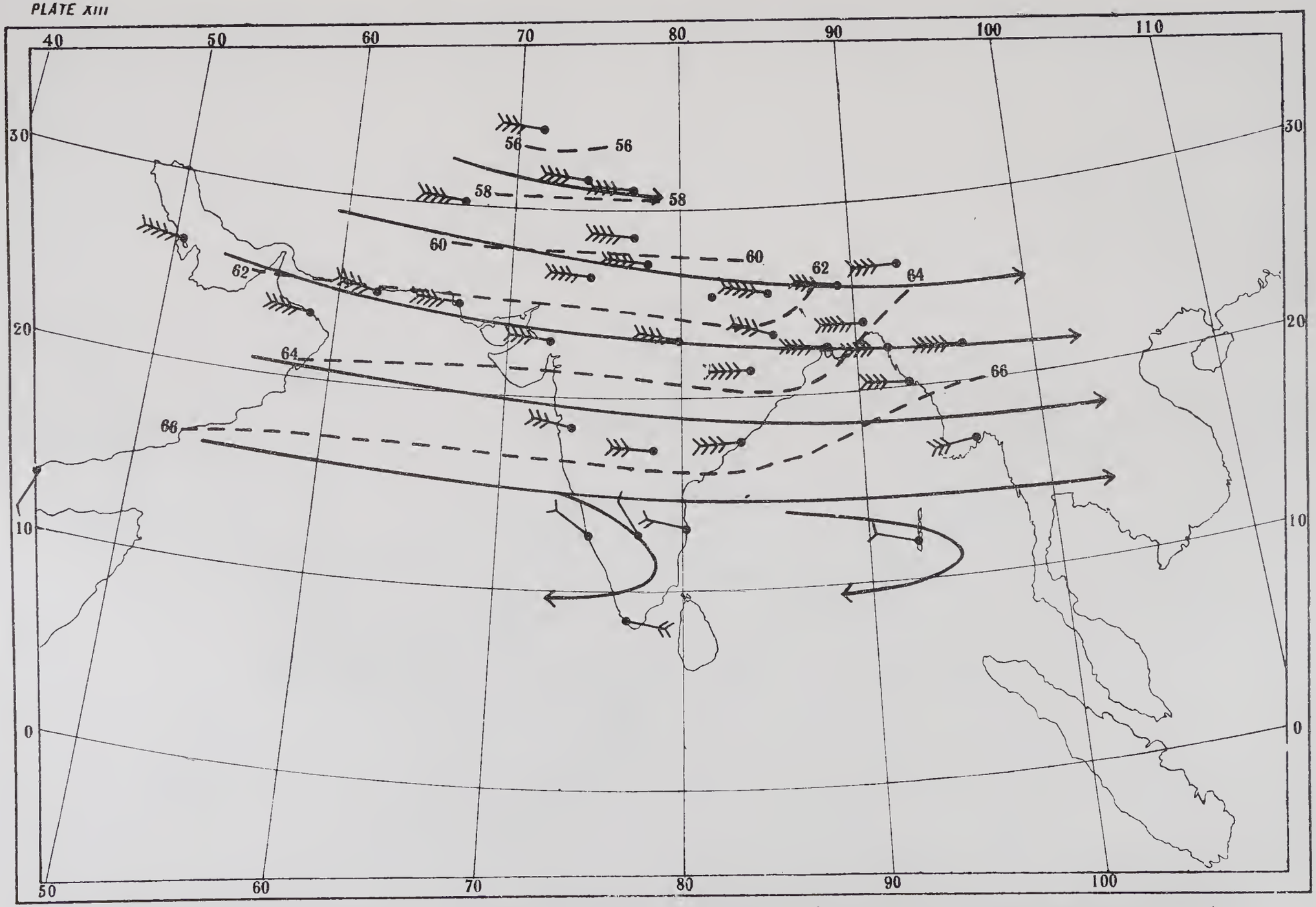


UPPER WINDS AND TEMPERATURES OVER INDIA —— FEBRUARY 3 KM.

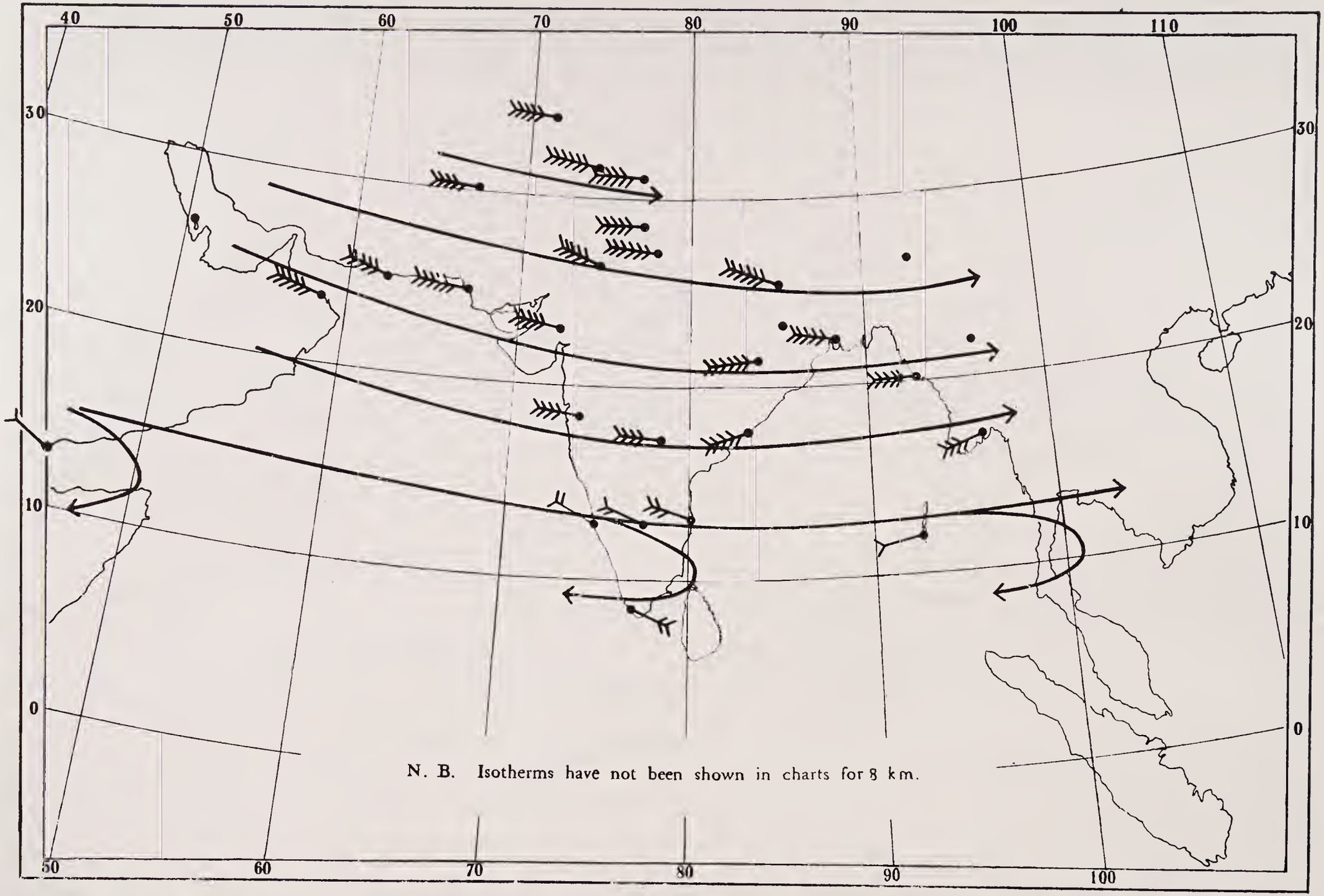


UPPER WINDS AND TEMPERATURES OVER INDIA —— FEBRUARY 4 KM.

PLATE XIII

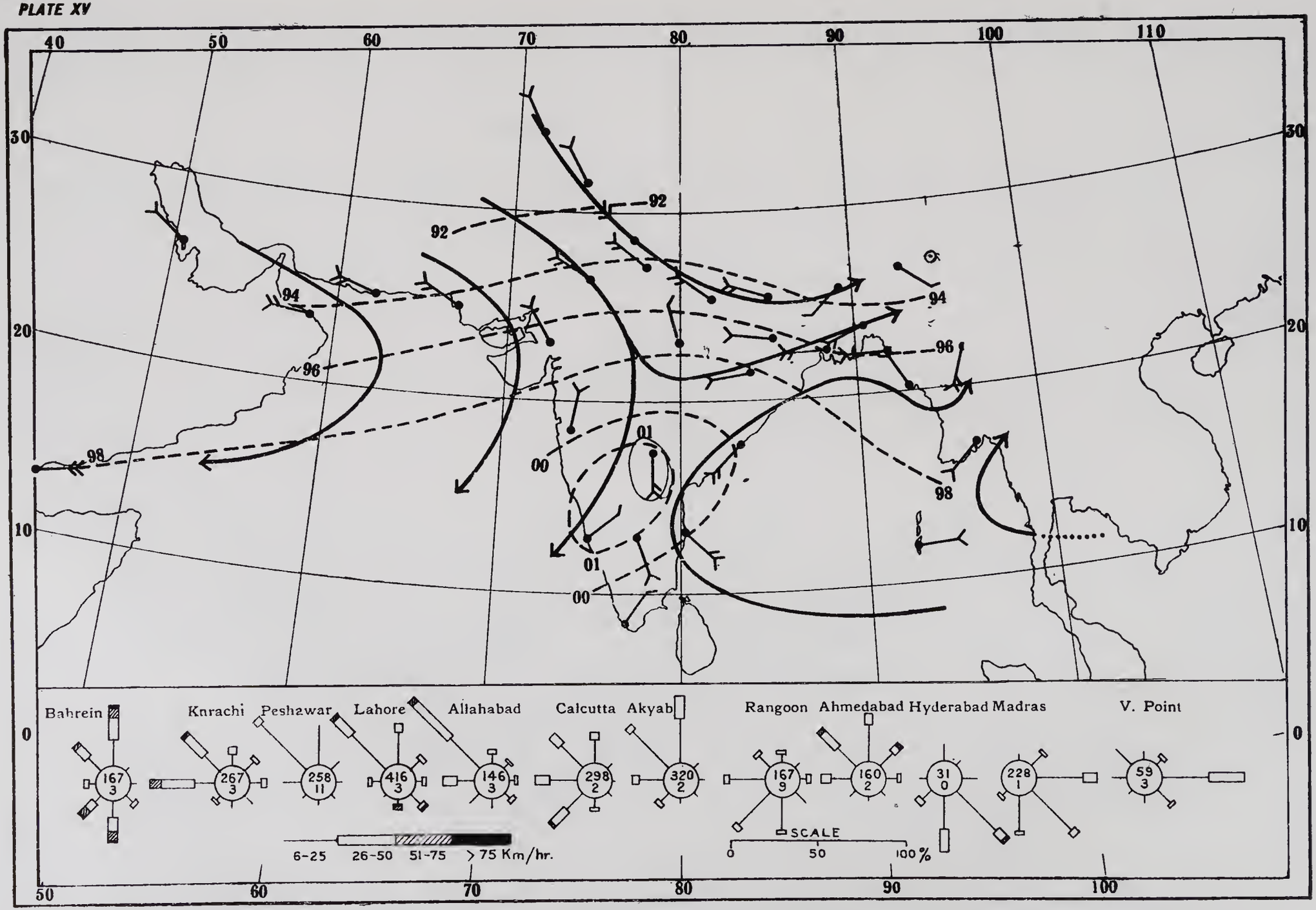


UPPER WINDS AND TEMPERATURES OVER INDIA —— FEBRUARY 6 KM.

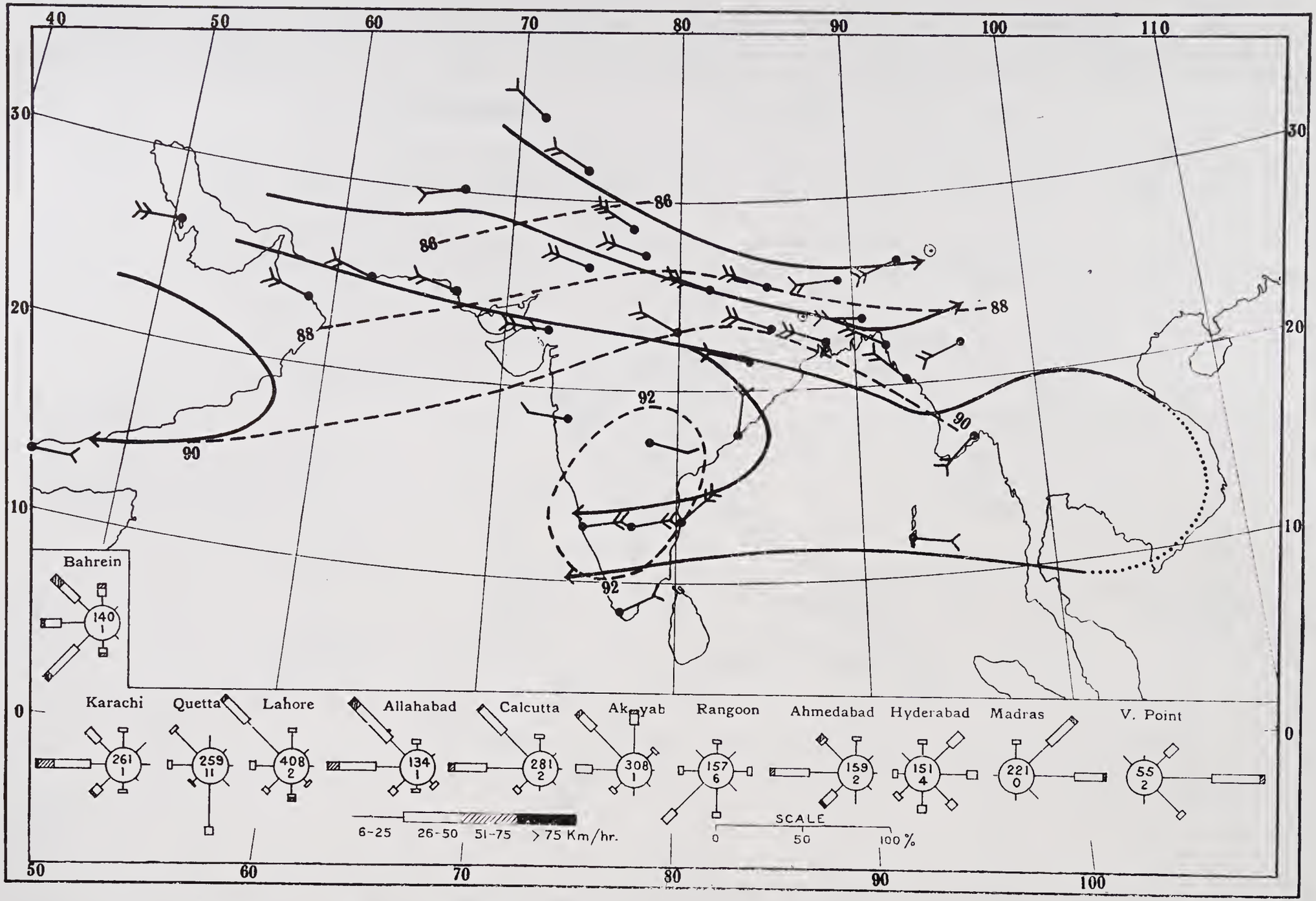


N. B. Isotherms have not been shown in charts for 8 km.

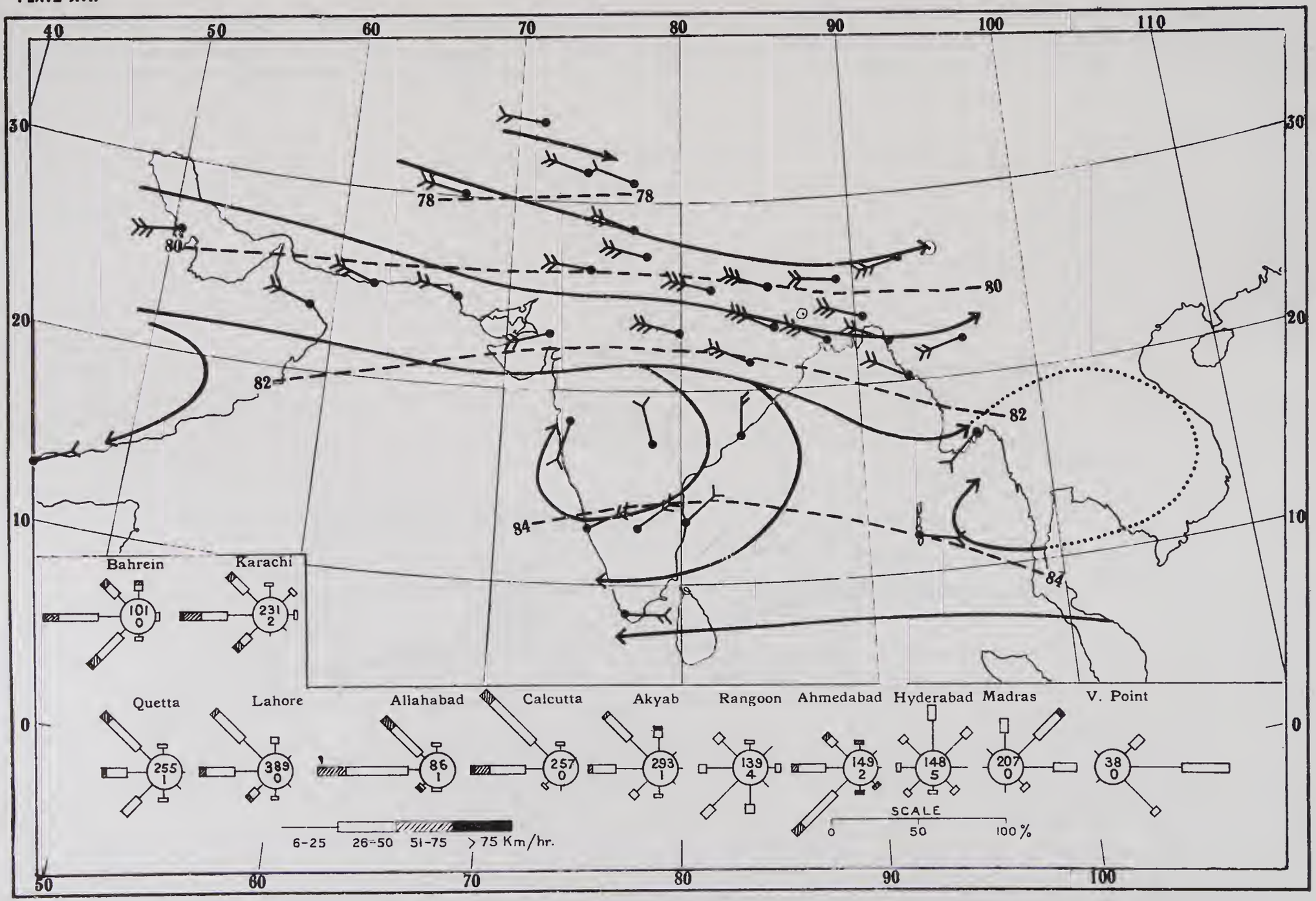
UPPER WINDS AND TEMPERATURES OVER INDIA ——— FEBRUARY 8 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— MARCH 1 KM.

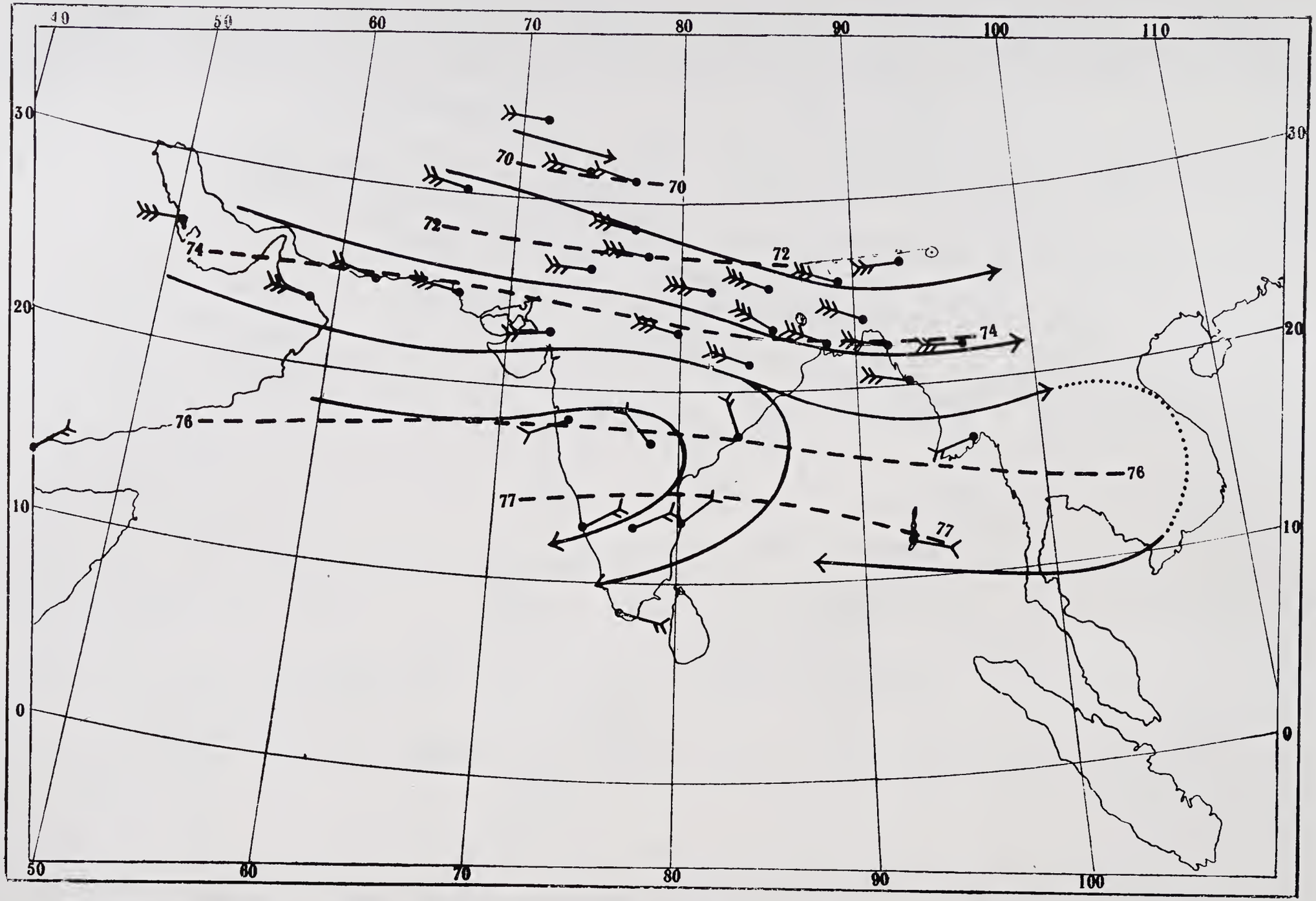


UPPER WINDS AND TEMPERATURES OVER INDIA —— MARCH 2 KM.

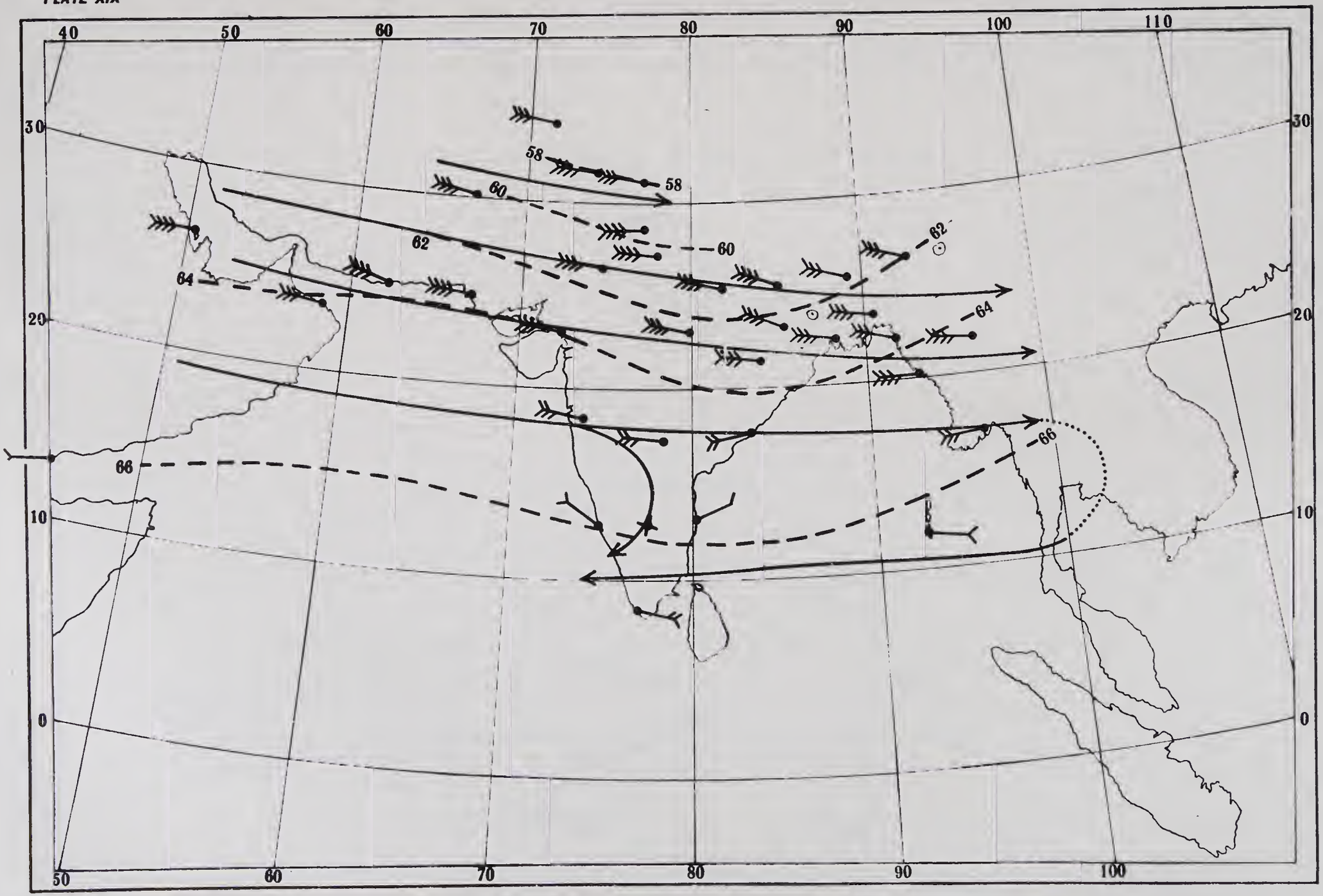


UPPER WINDS AND TEMPERATURES OVER INDIA —— MARCH 3 KM.

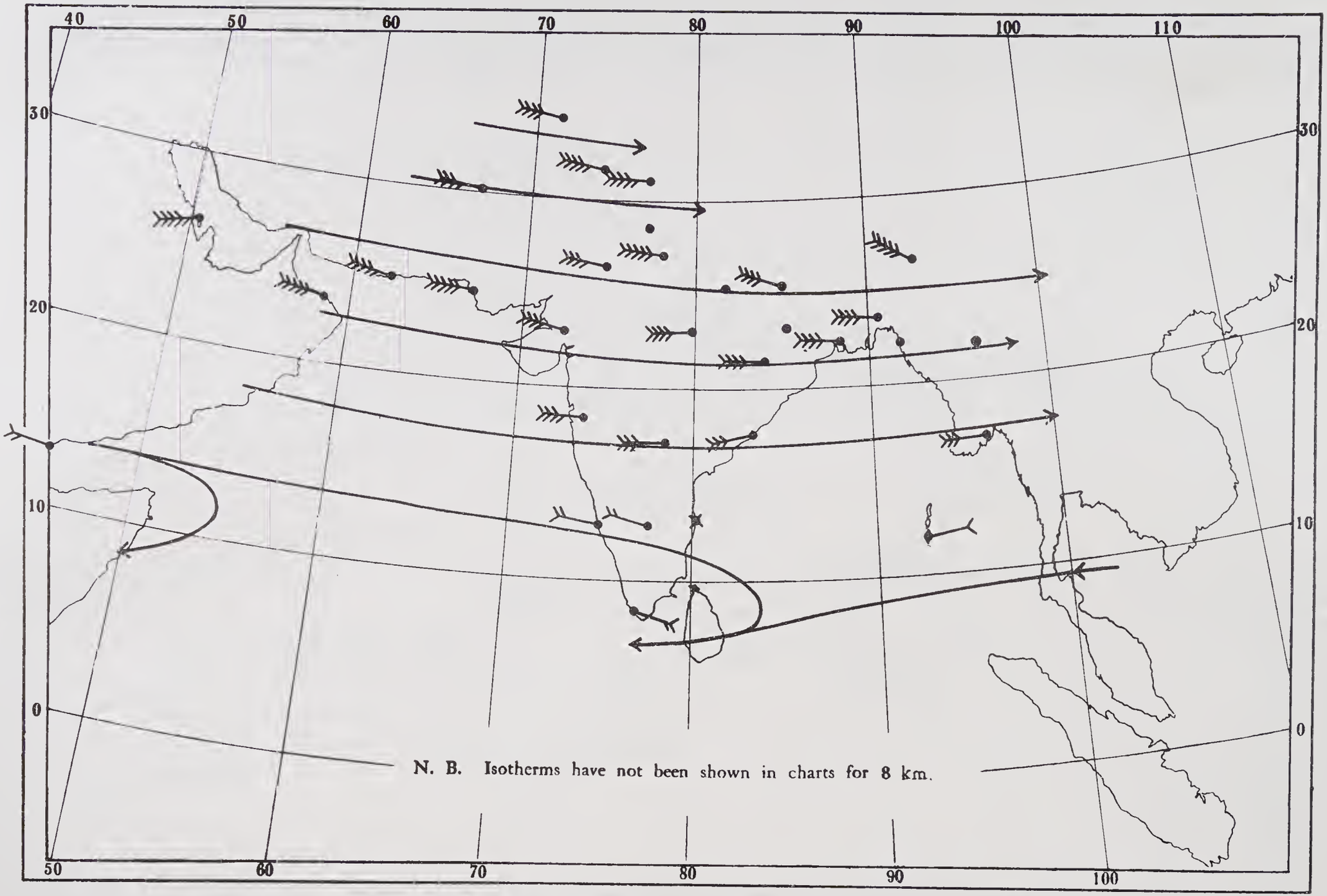
PLATE XVIII



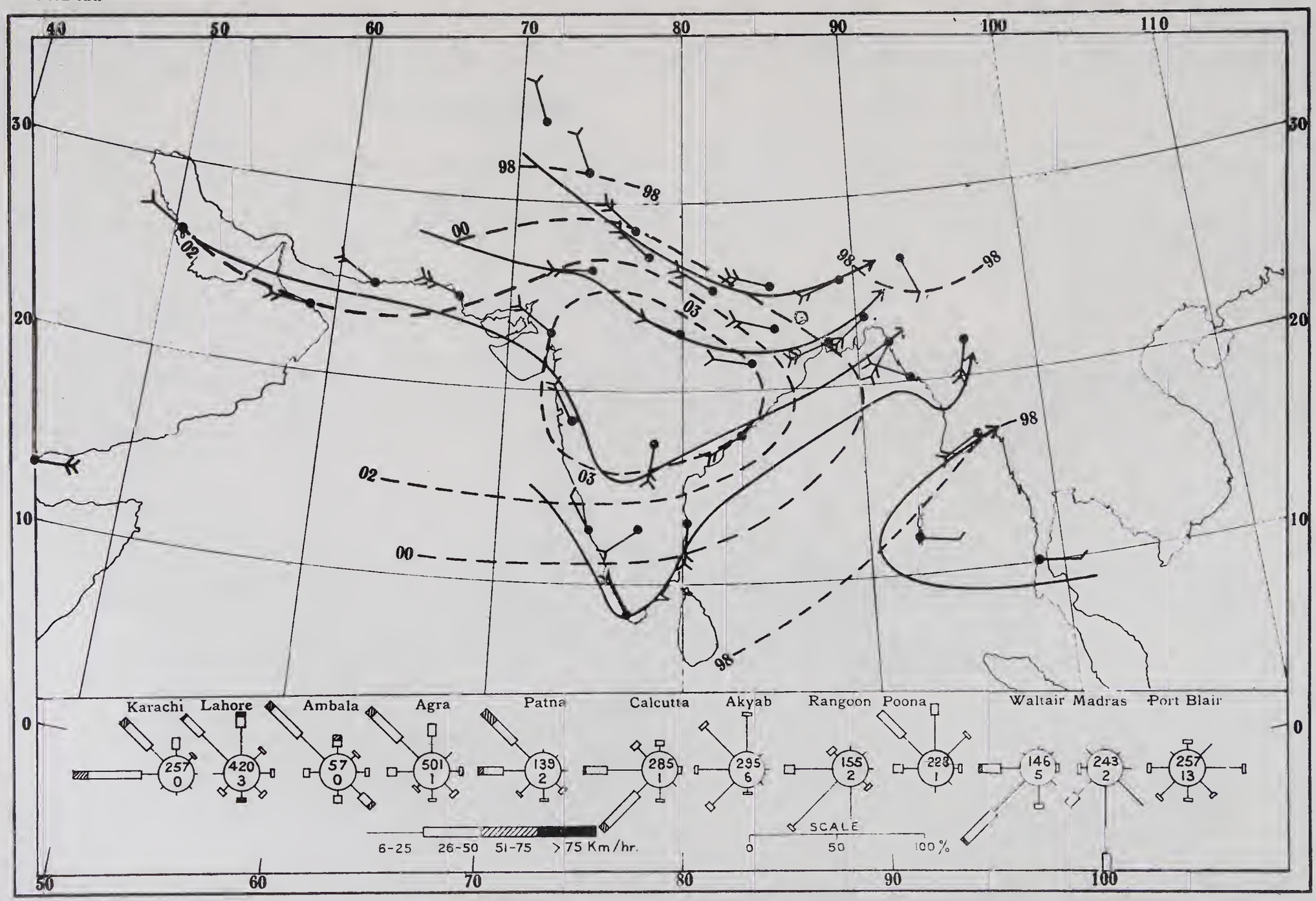
UPPER WINDS AND TEMPERATURES OVER INDIA —— MARCH 4 KM.



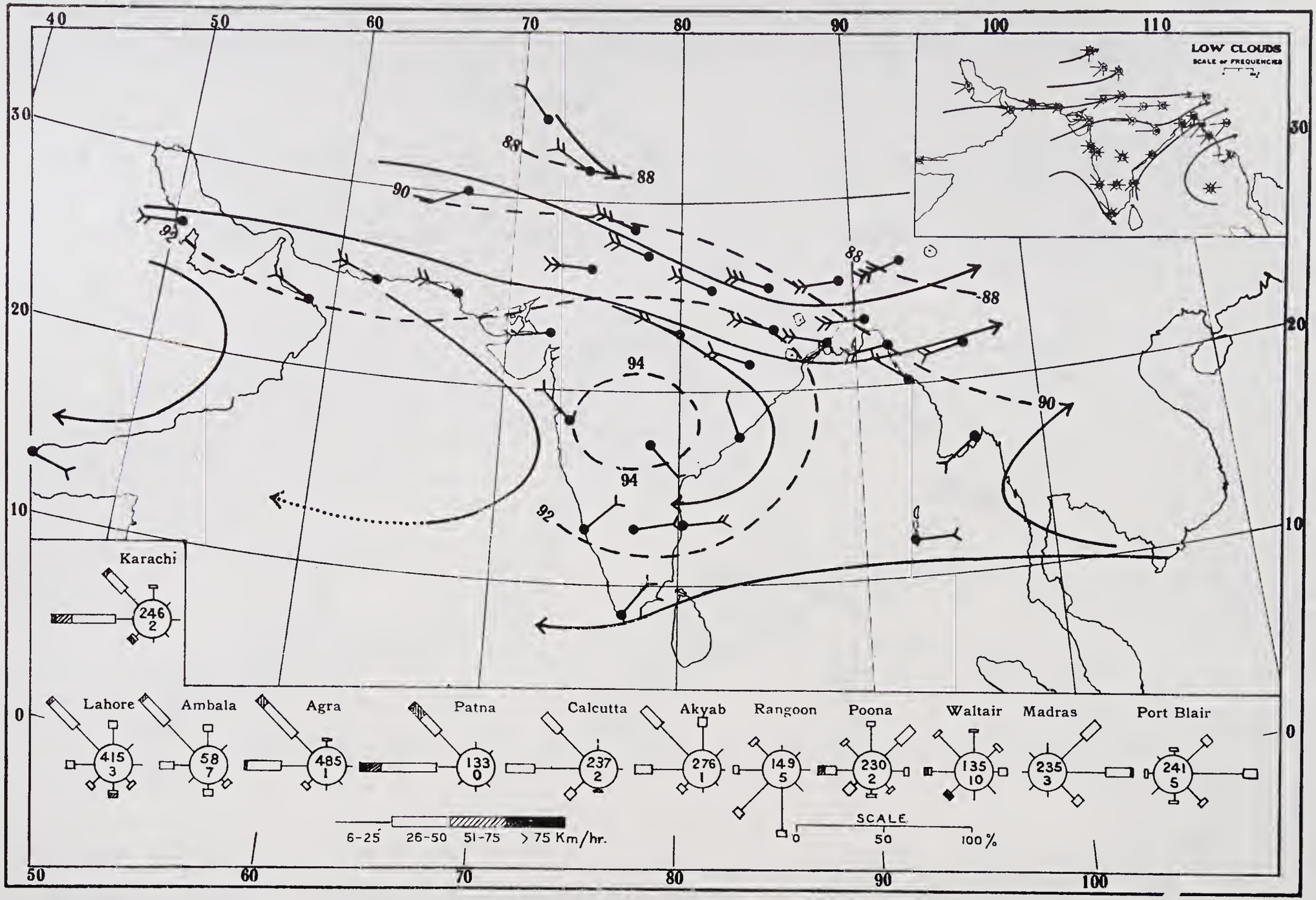
UPPER WINDS AND TEMPERATURES OVER INDIA —— MARCH 6 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— MARCH 8 KM.

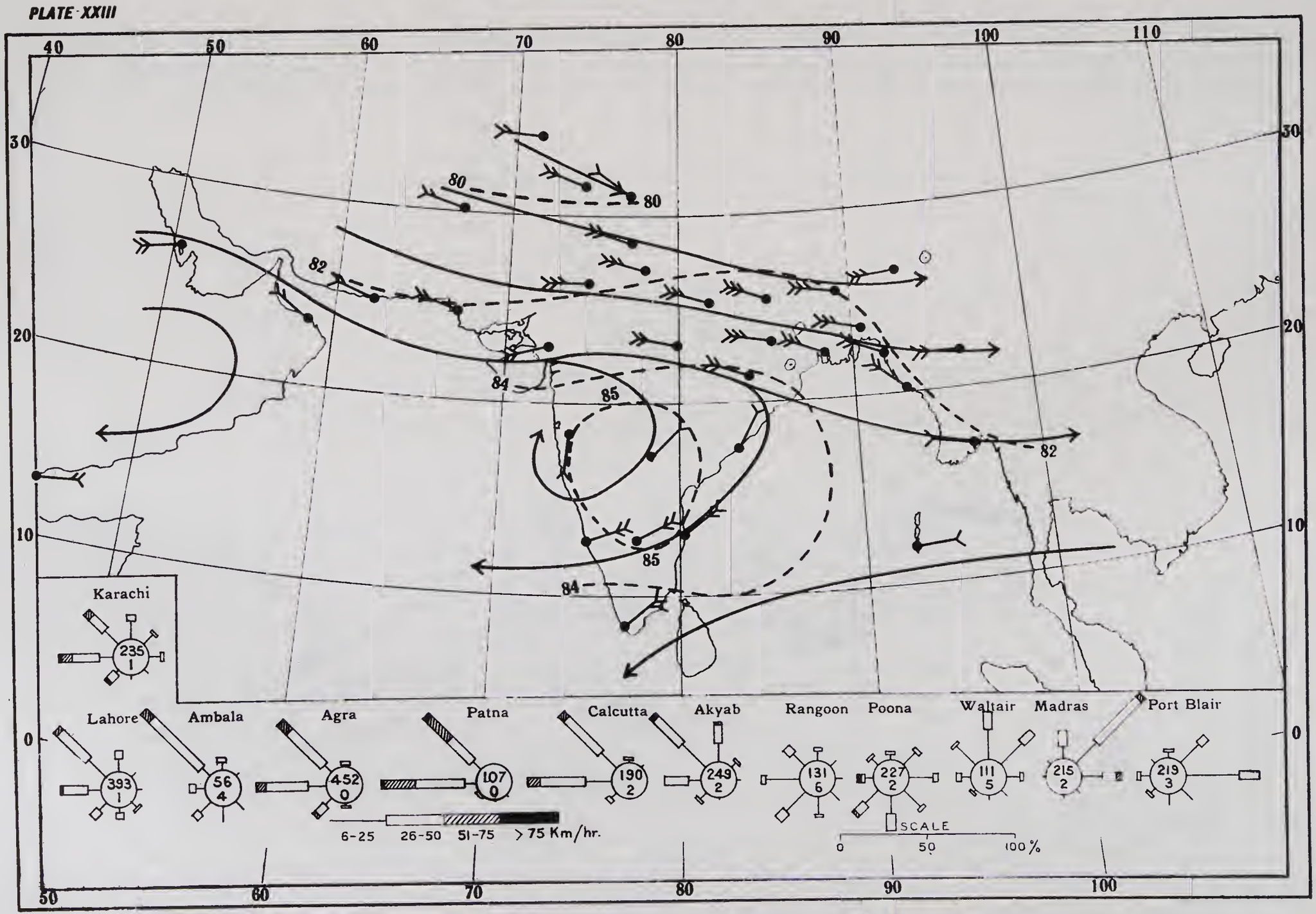


UPPER WINDS AND TEMPERATURES OVER INDIA —— APRIL 1 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— APRIL 2 KM.

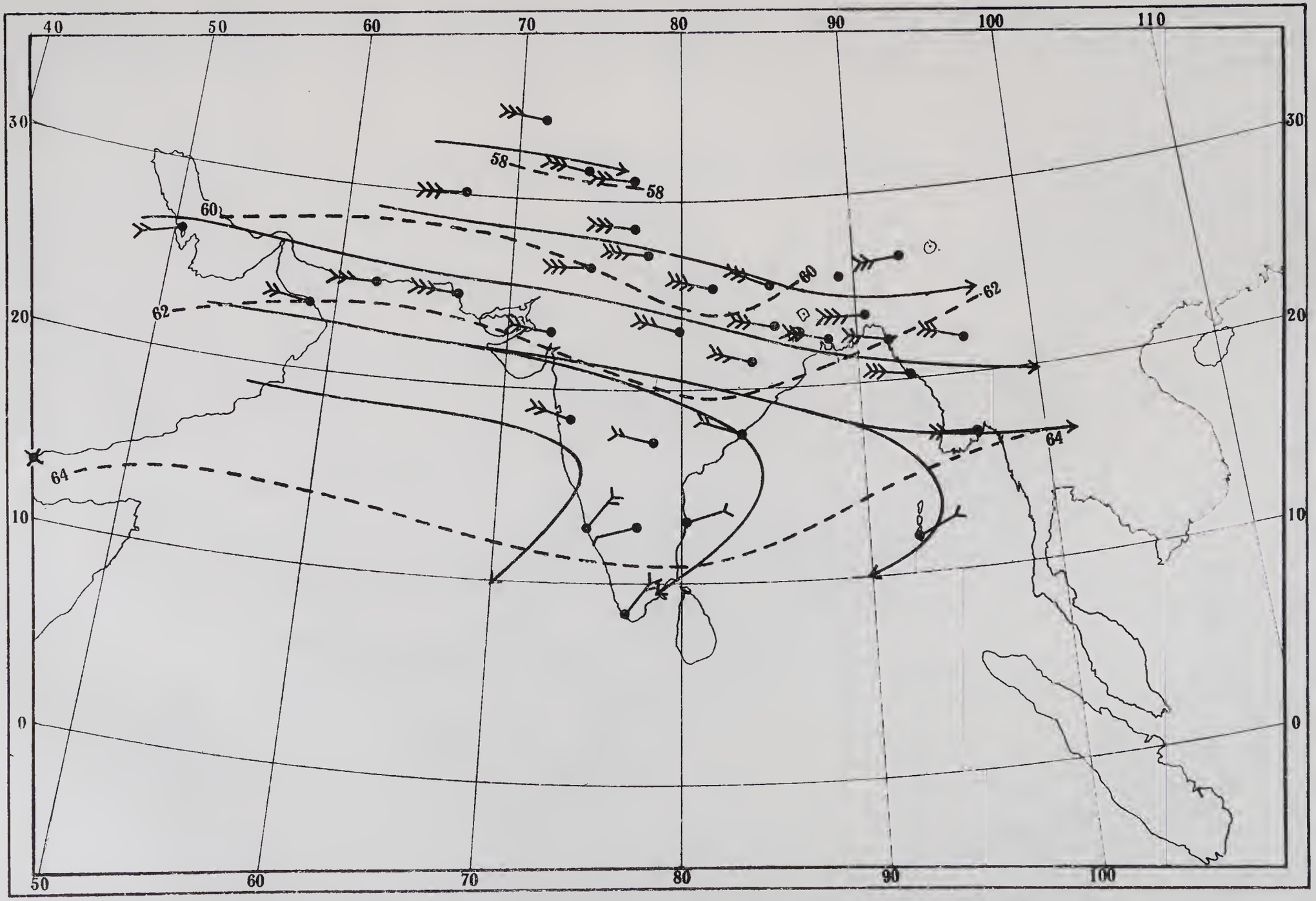
PLATE XXIII



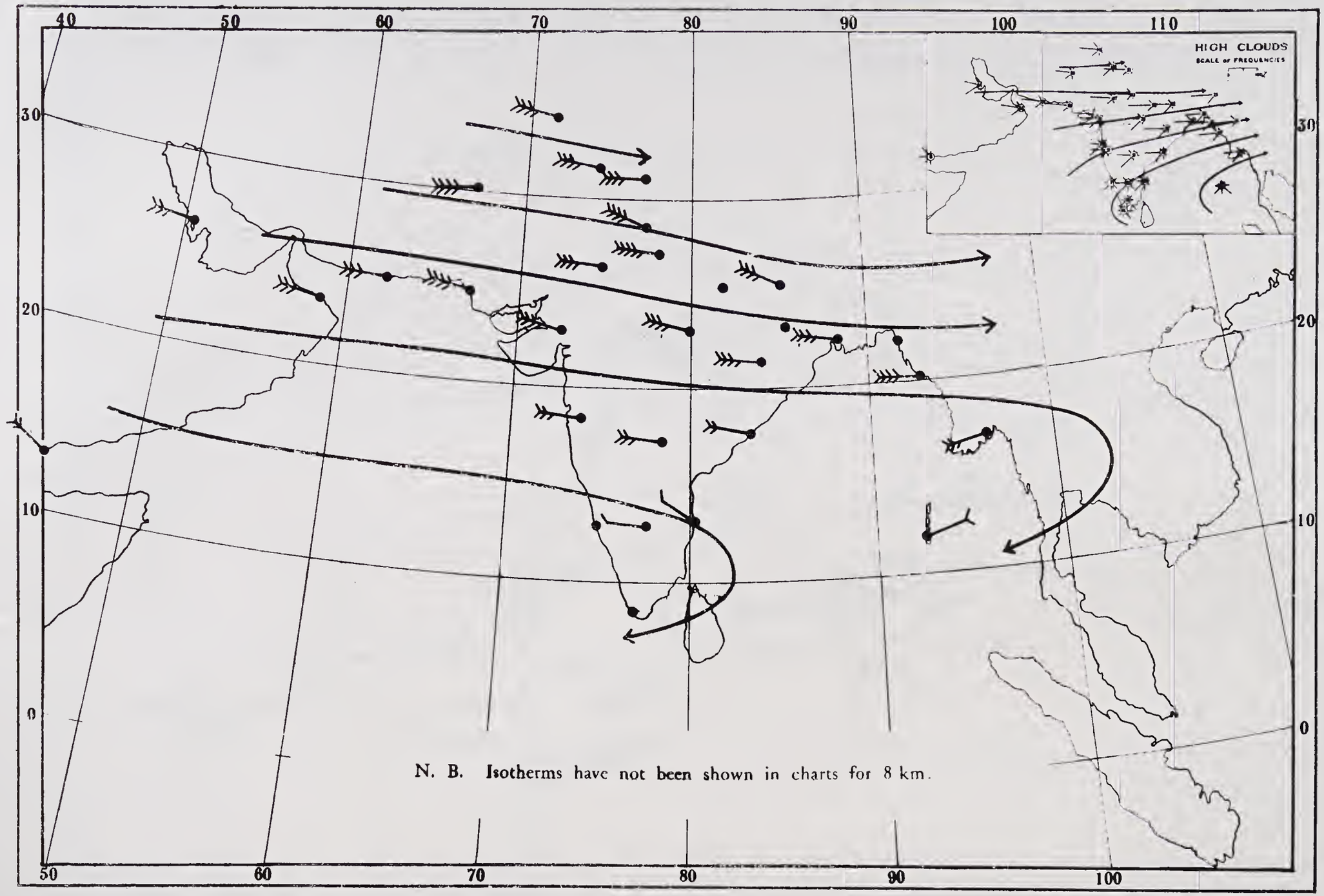
UPPER WINDS AND TEMPERATURES OVER INDIA —— APRIL 3 KM.

UPPER WINDS AND TEMPERATURES OVER INDIA —— APRIL 4 KM.

PLATE XXV

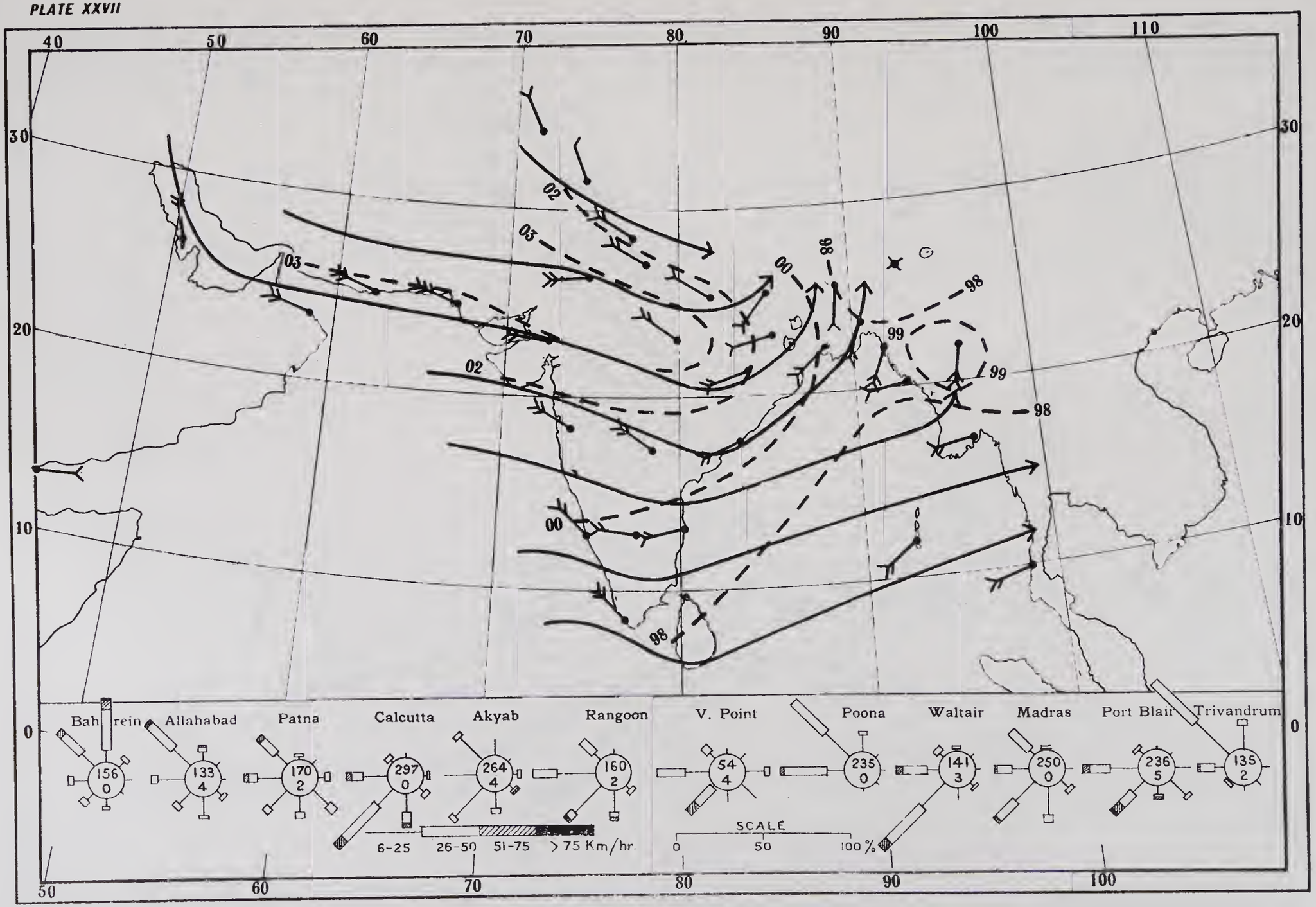


UPPER WINDS AND TEMPERATURES OVER INDIA —— APRIL 6 KM.

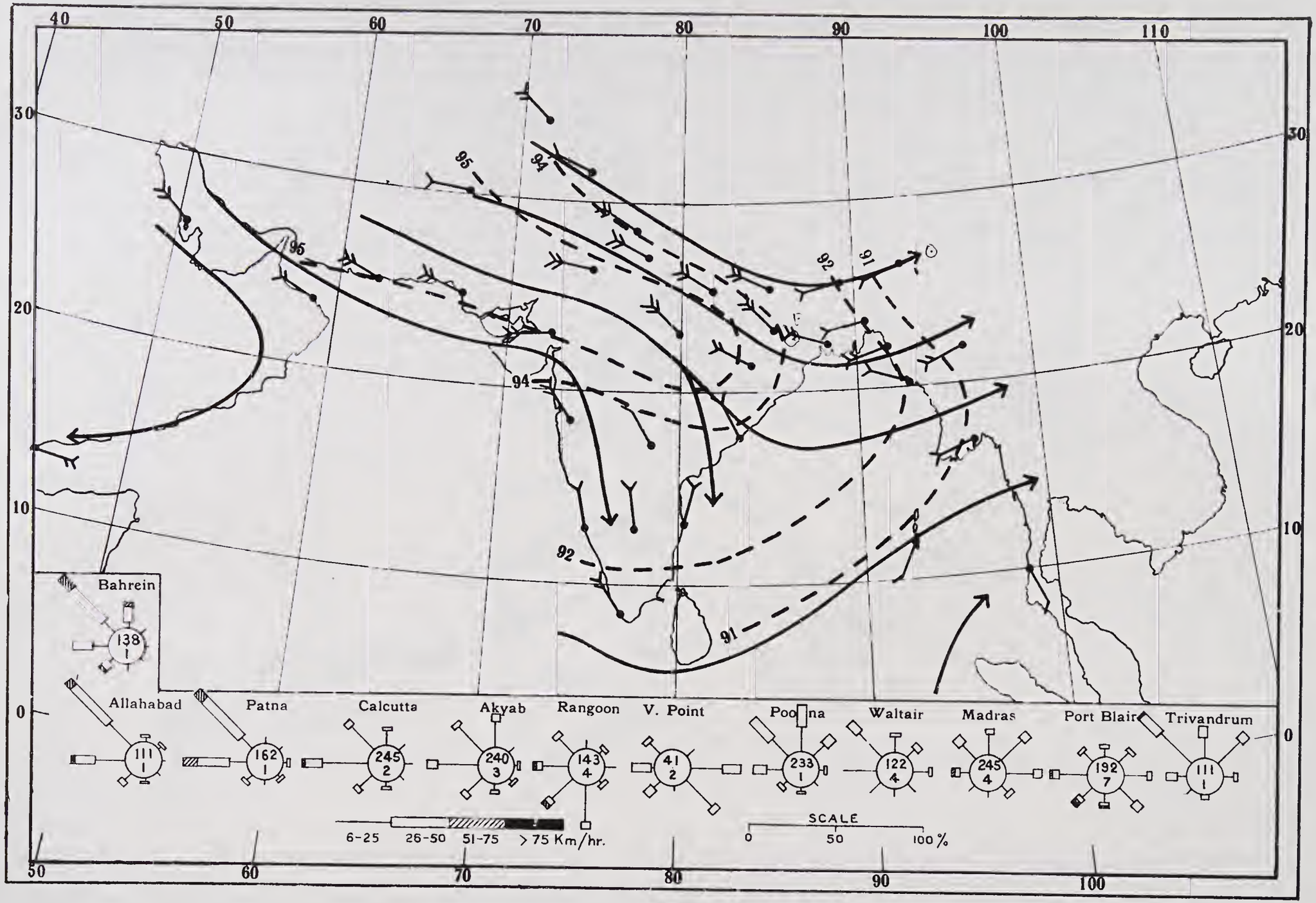


N. B. Isotherms have not been shown in charts for 8 km.

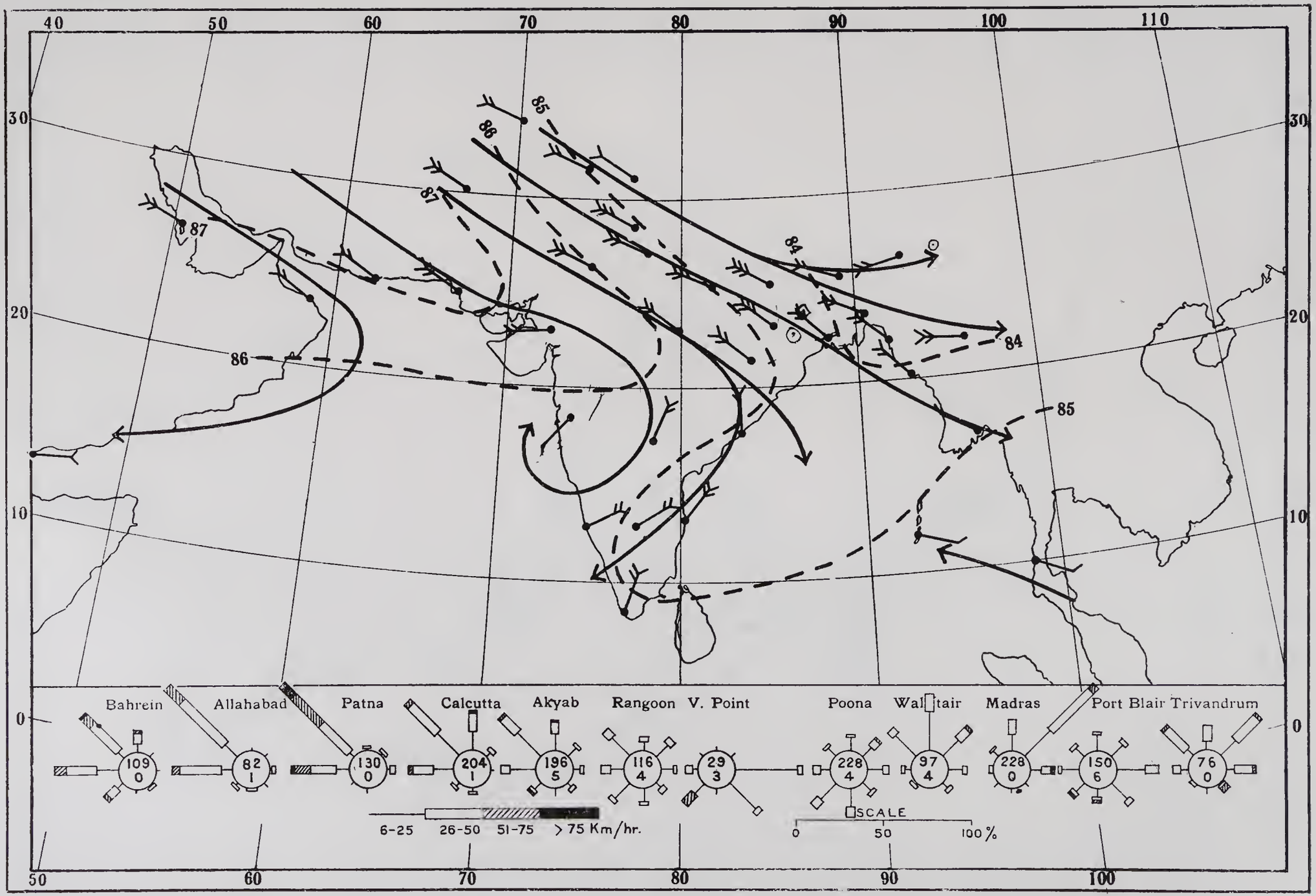
UPPER WINDS AND TEMPERATURES OVER INDIA —— APRIL 8 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA ——— MAY 1 KM.

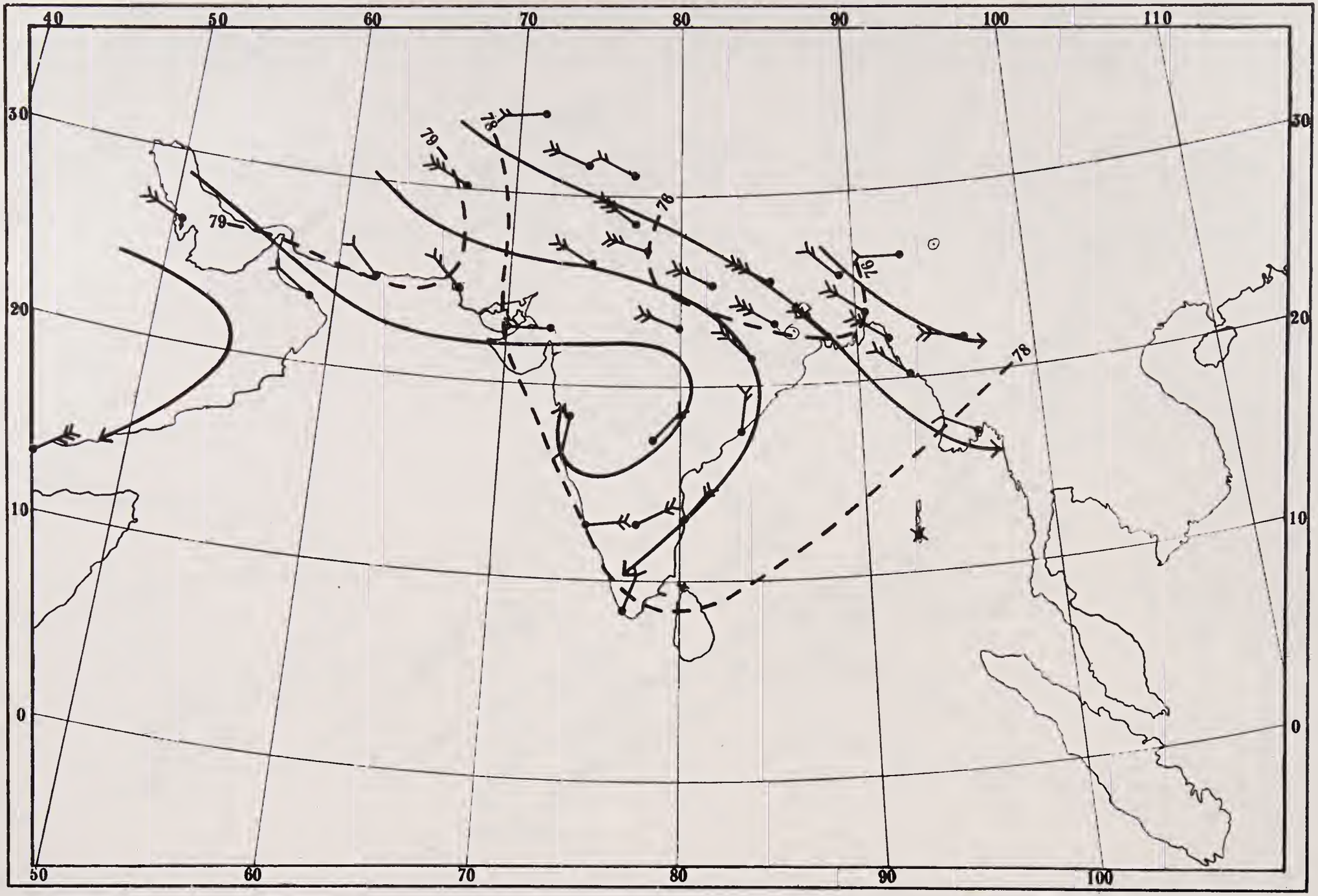


UPPER WINDS AND TEMPERATURES OVER INDIA —— MAY 2 KM.

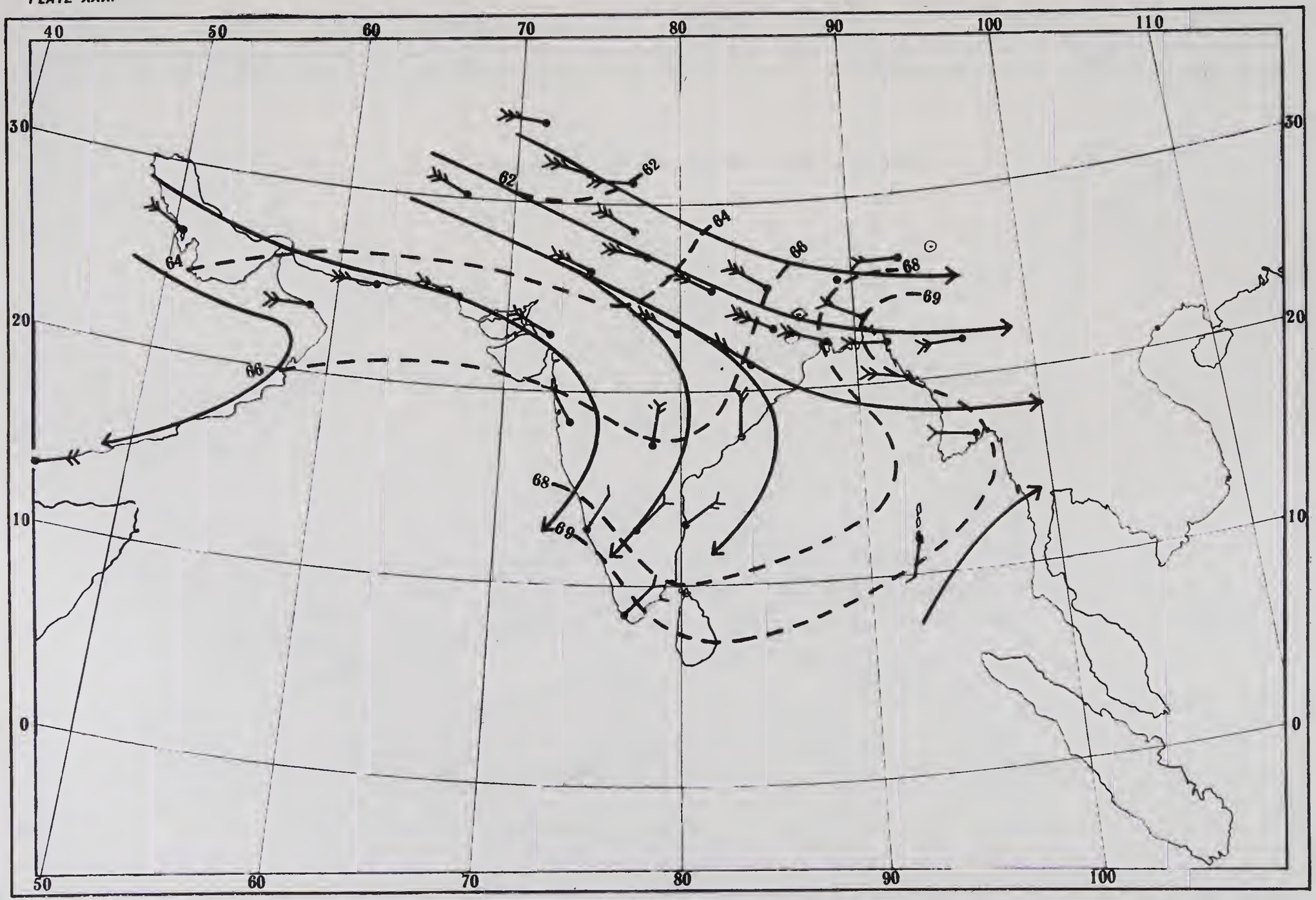


UPPER WINDS AND TEMPERATURES OVER INDIA —— MAY 3 KM.

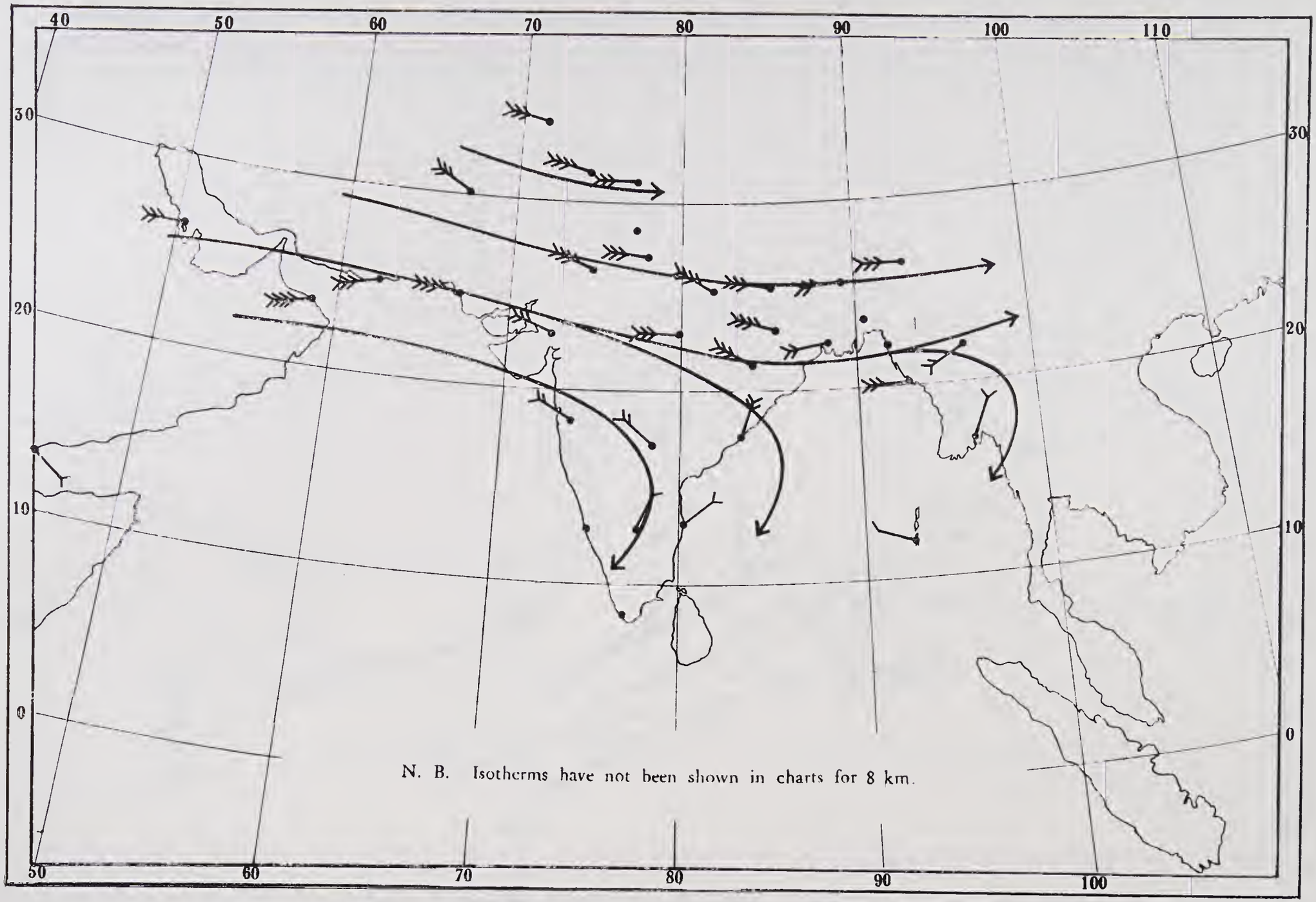
PLATE XXX



UPPER WINDS AND TEMPERATURES OVER INDIA —— MAY 4 KM.

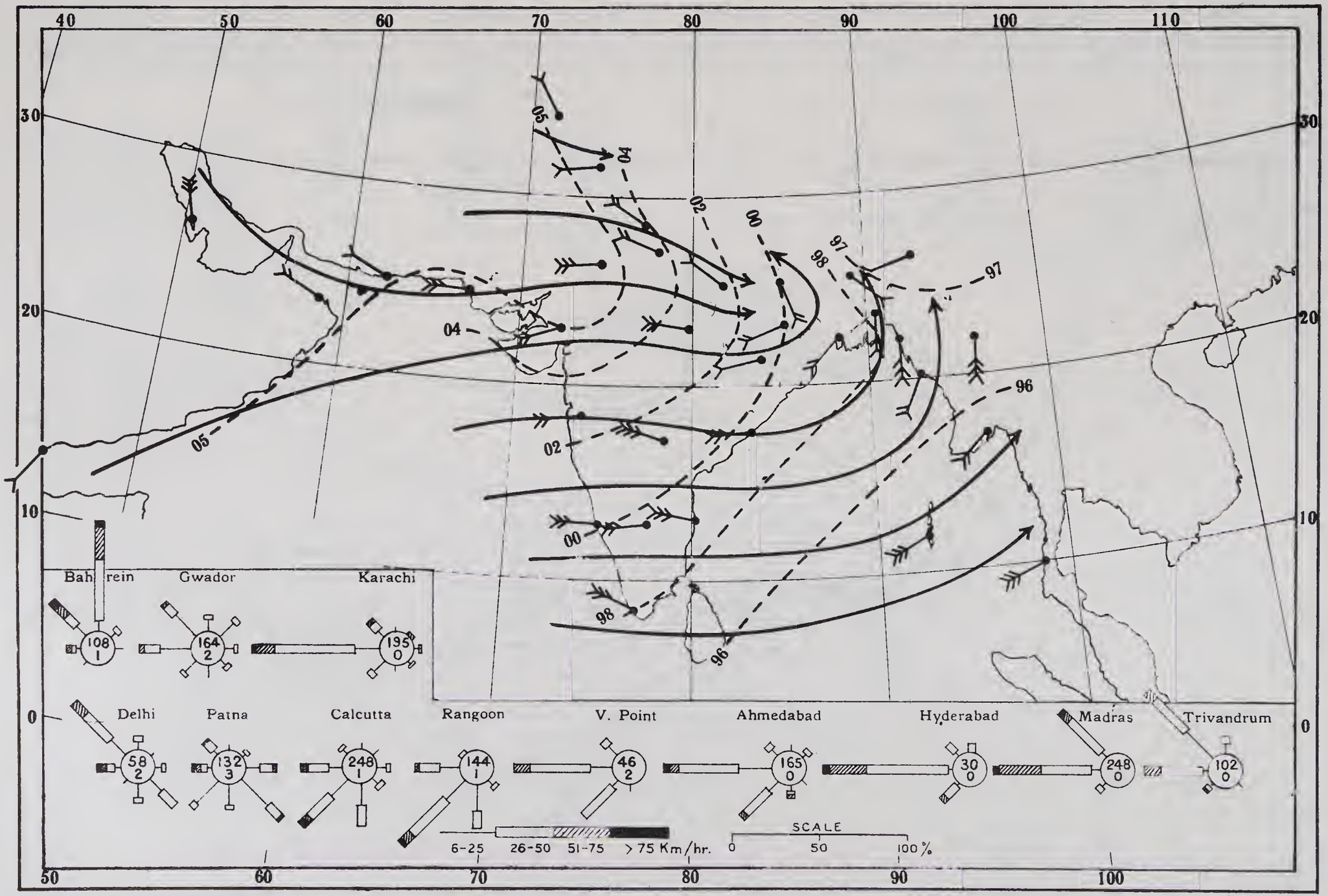


UPPER WINDS AND TEMPERATURES OVER INDIA —— MAY 6 KM.



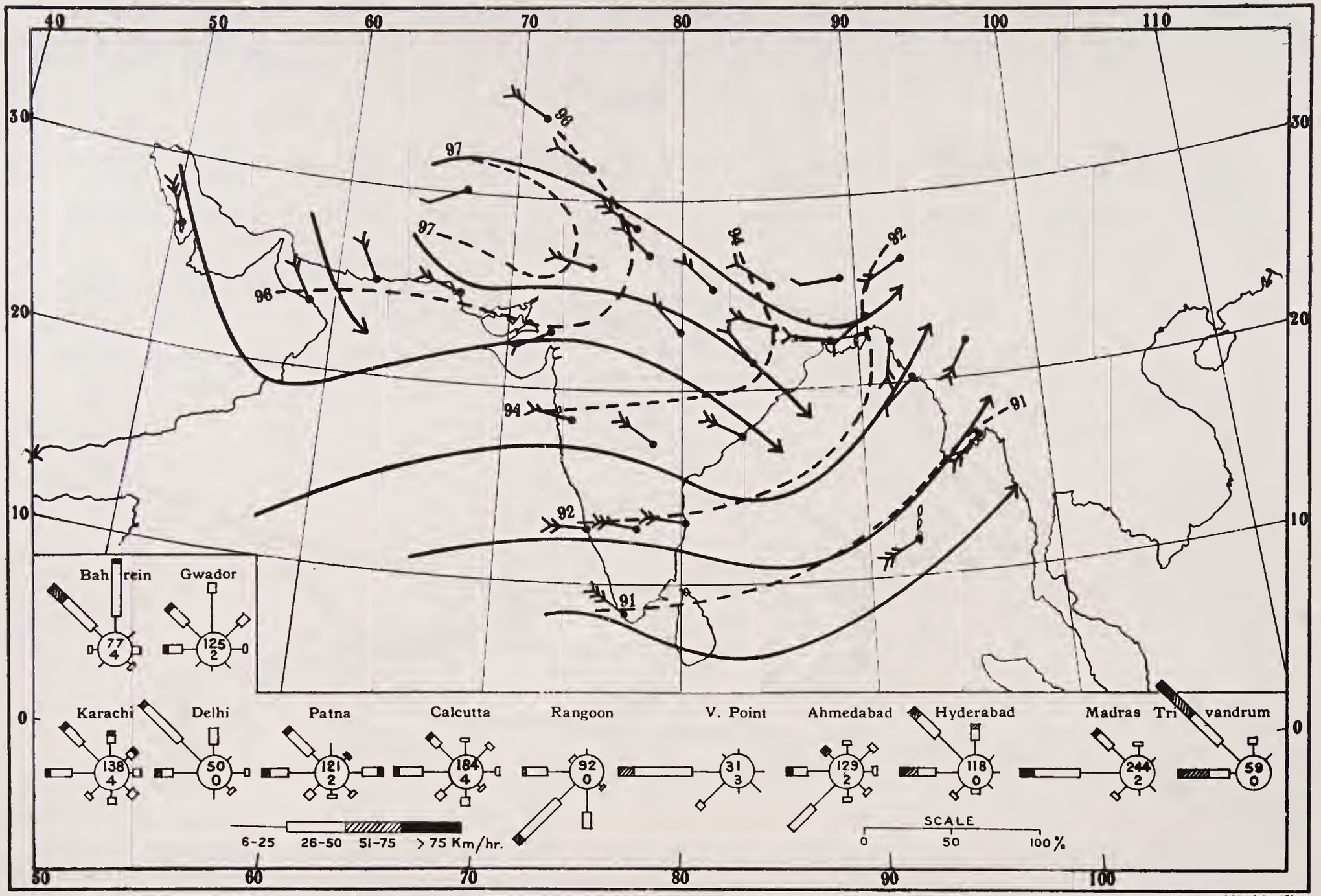
N. B. Isotherms have not been shown in charts for 8 km.

UPPER WINDS AND TEMPERATURES OVER INDIA —— MAY 8 KM.

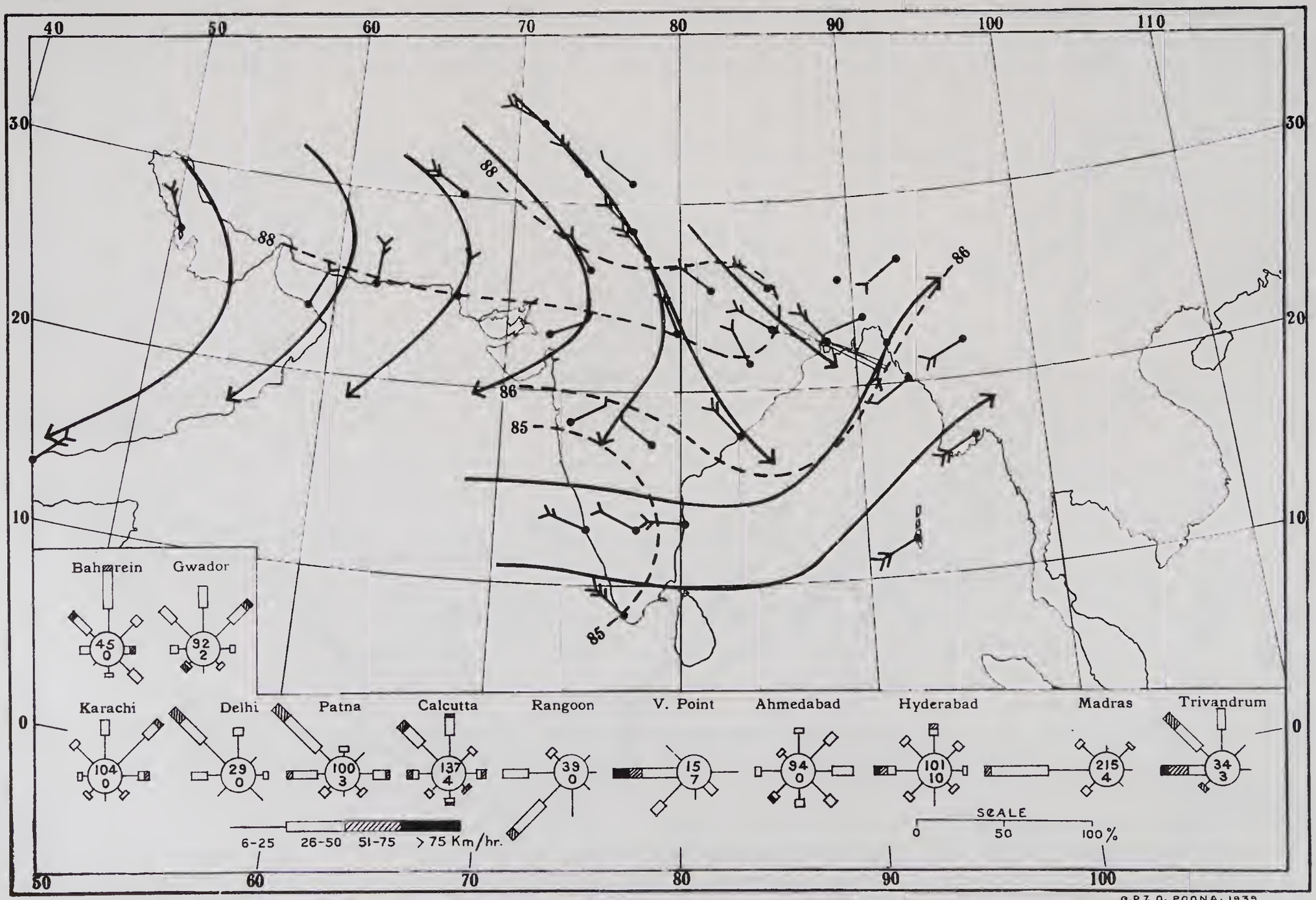


G.P.Z.O. POONA, 1939.

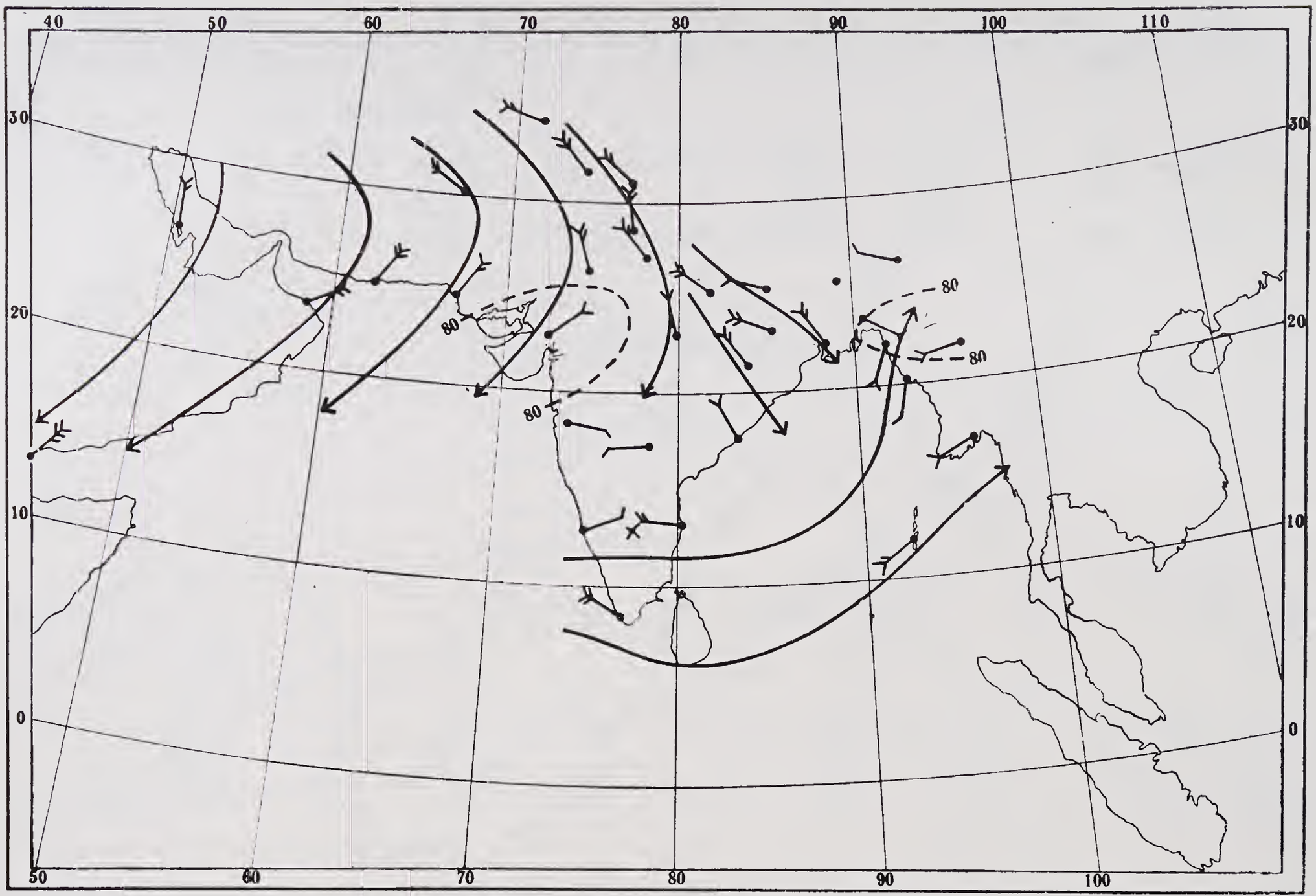
UPPER WINDS AND TEMPERATURES OVER INDIA —— JUNE 1 KM.



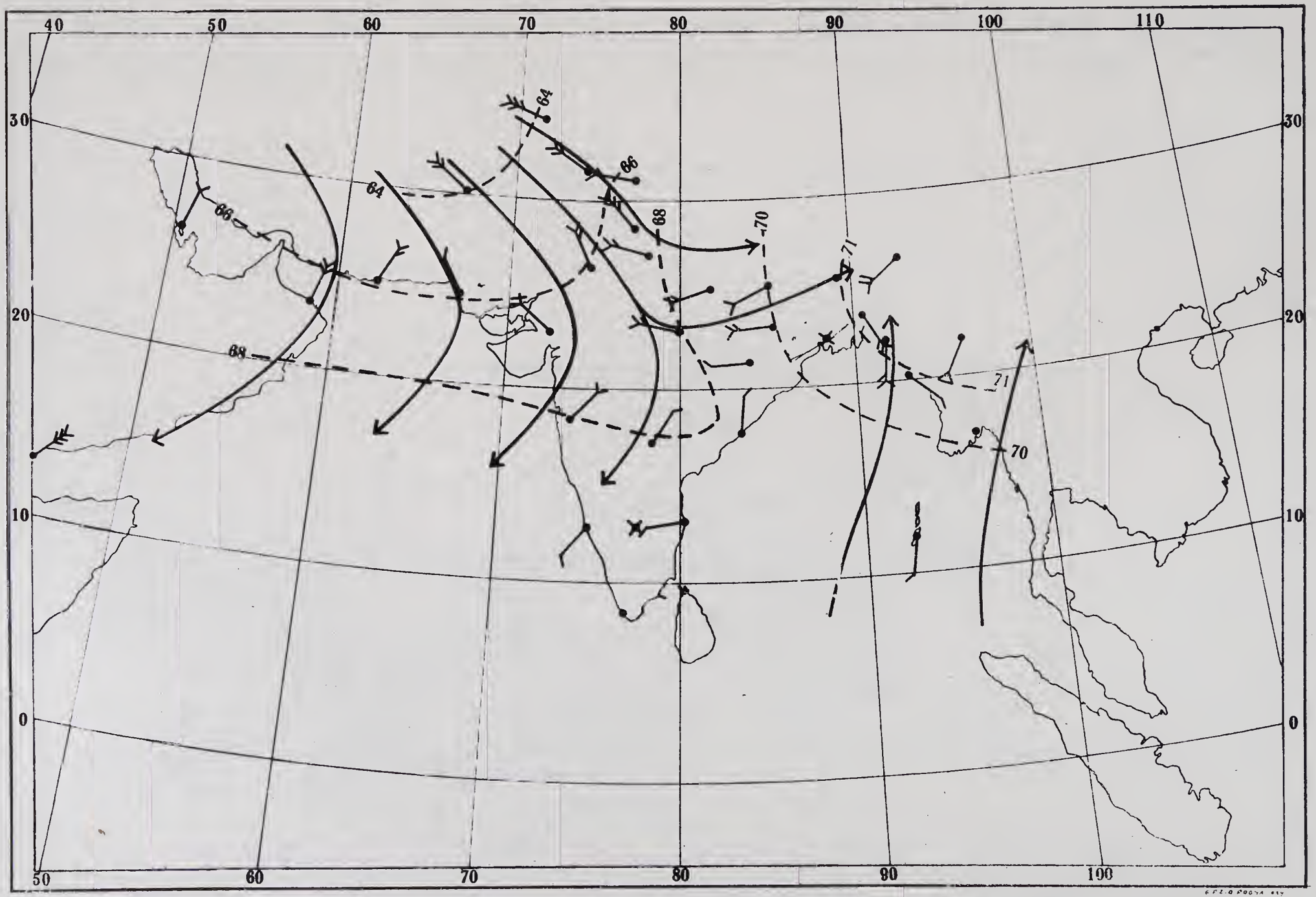
UPPER WINDS AND TEMPERATURES OVER INDIA —— JUNE 2 KM.



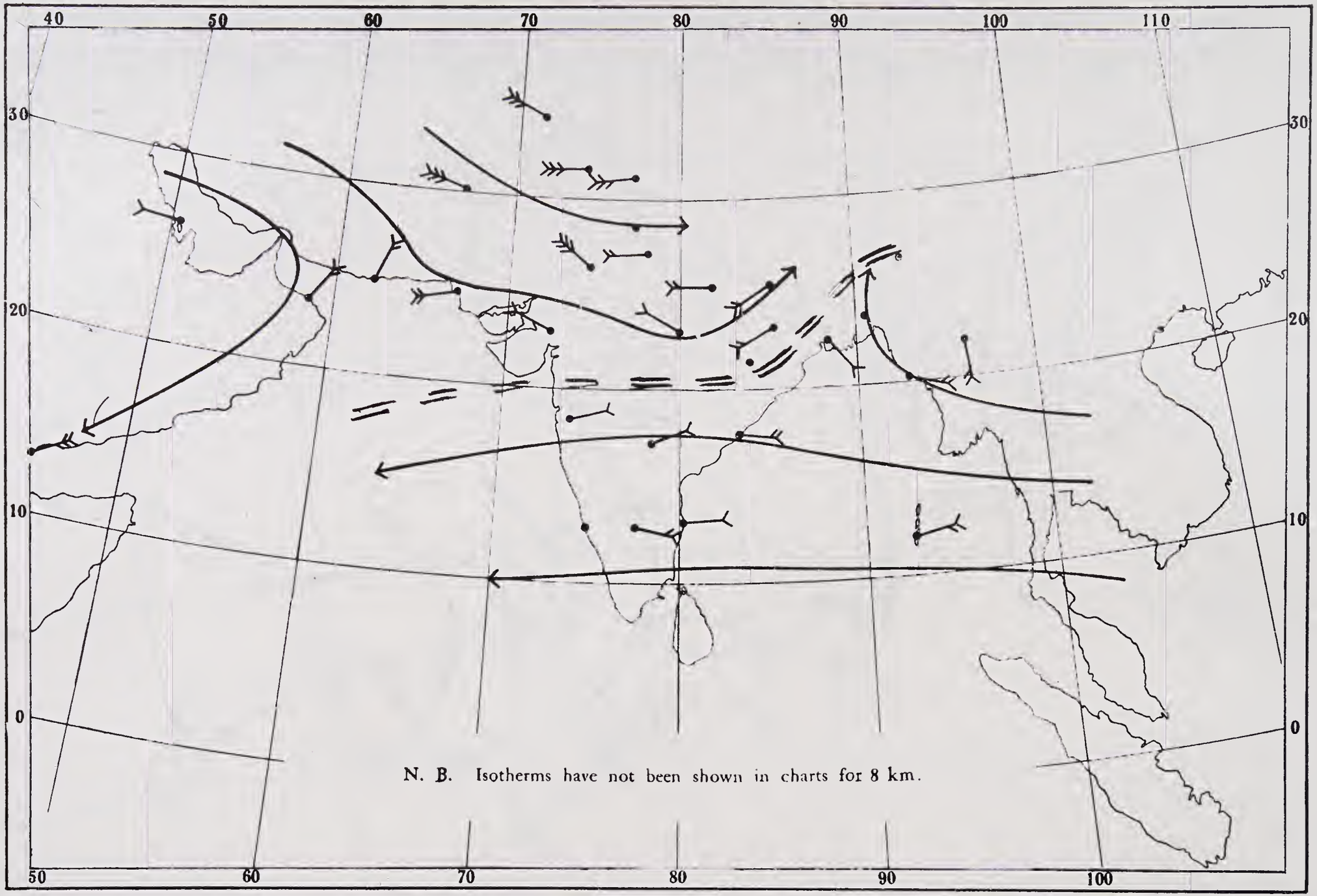
UPPER WINDS AND TEMPERATURES OVER INDIA —— JUNE 3 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— JUNE 4 KM.

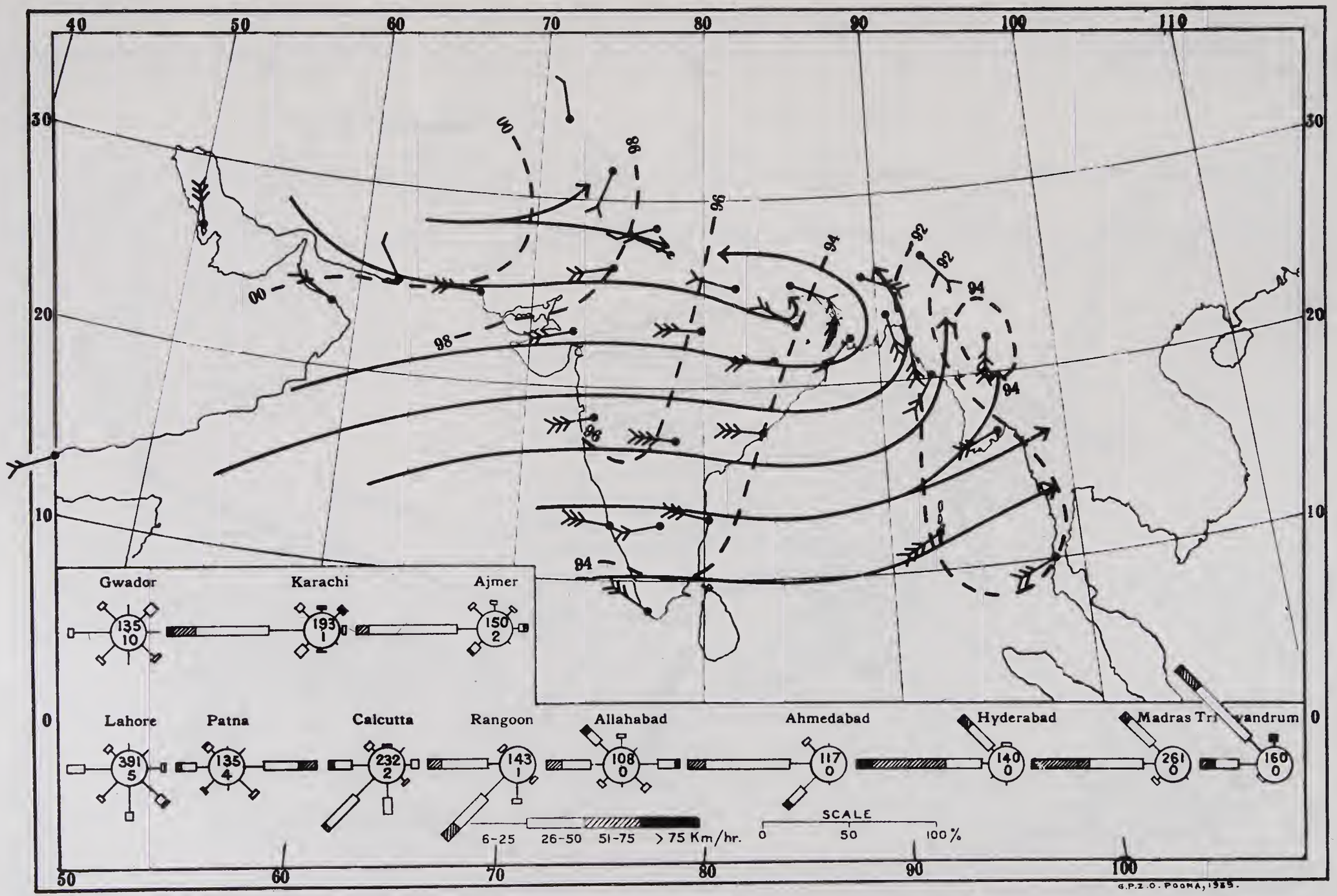


UPPER WINDS AND TEMPERATURES OVER INDIA —— JUNE 6 KM.



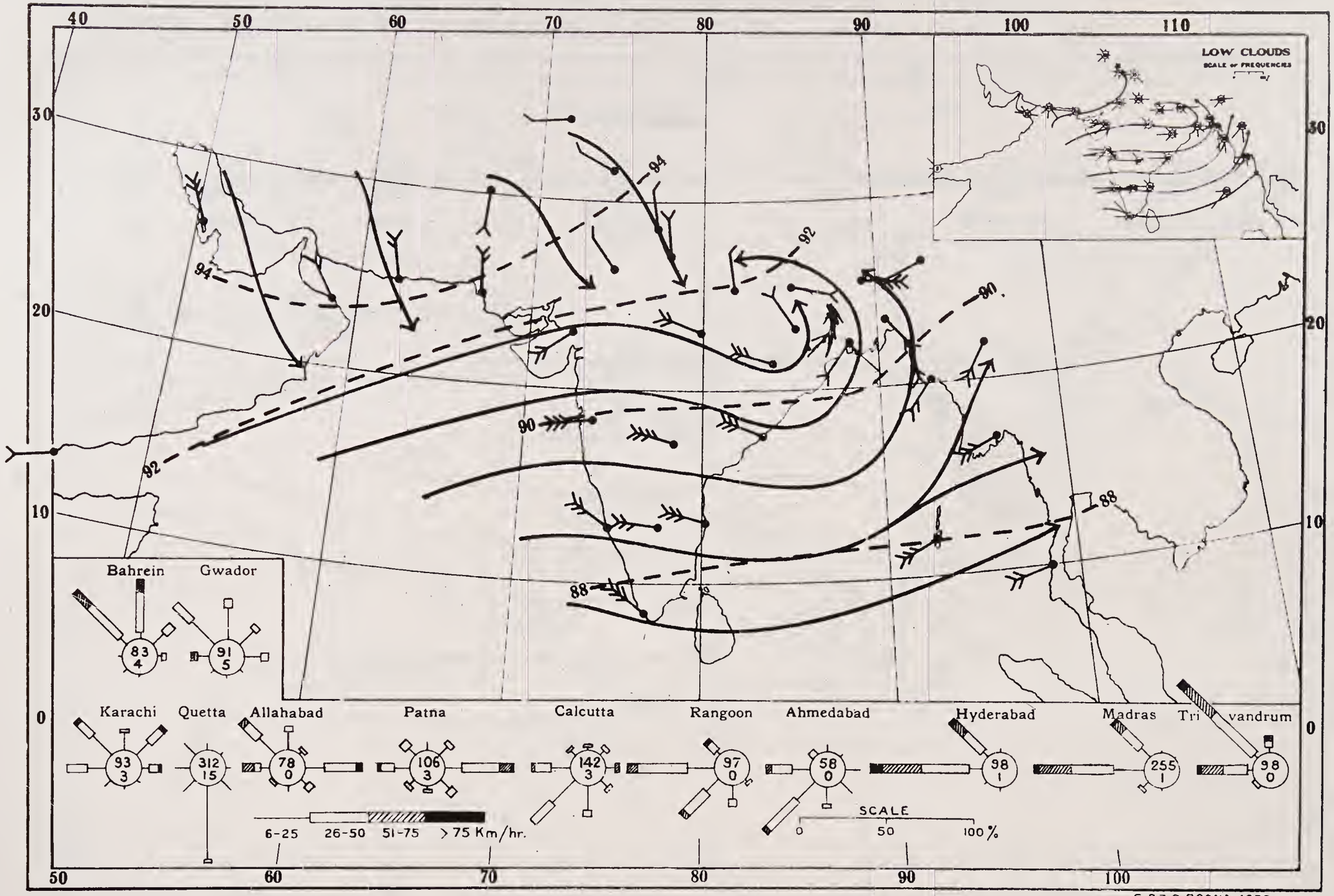
N. B. Isotherms have not been shown in charts for 8 km.

UPPER WINDS AND TEMPERATURES OVER INDIA —— JUNE 8 KM.



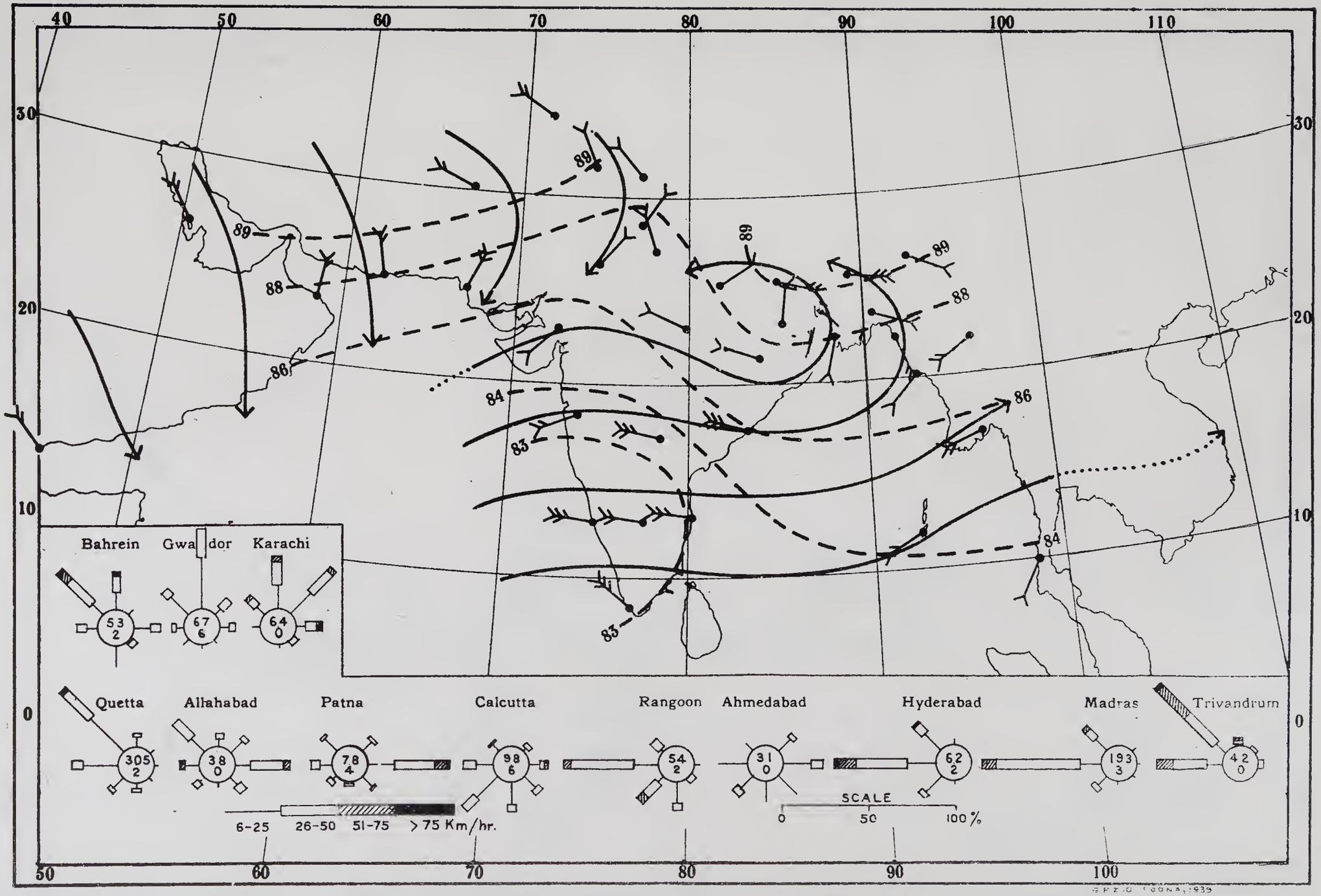
UPPER WINDS AND TEMPERATURES OVER INDIA —— JULY 1 KM.

PLATE XL



G. P. Z. O. POONA, 1939.

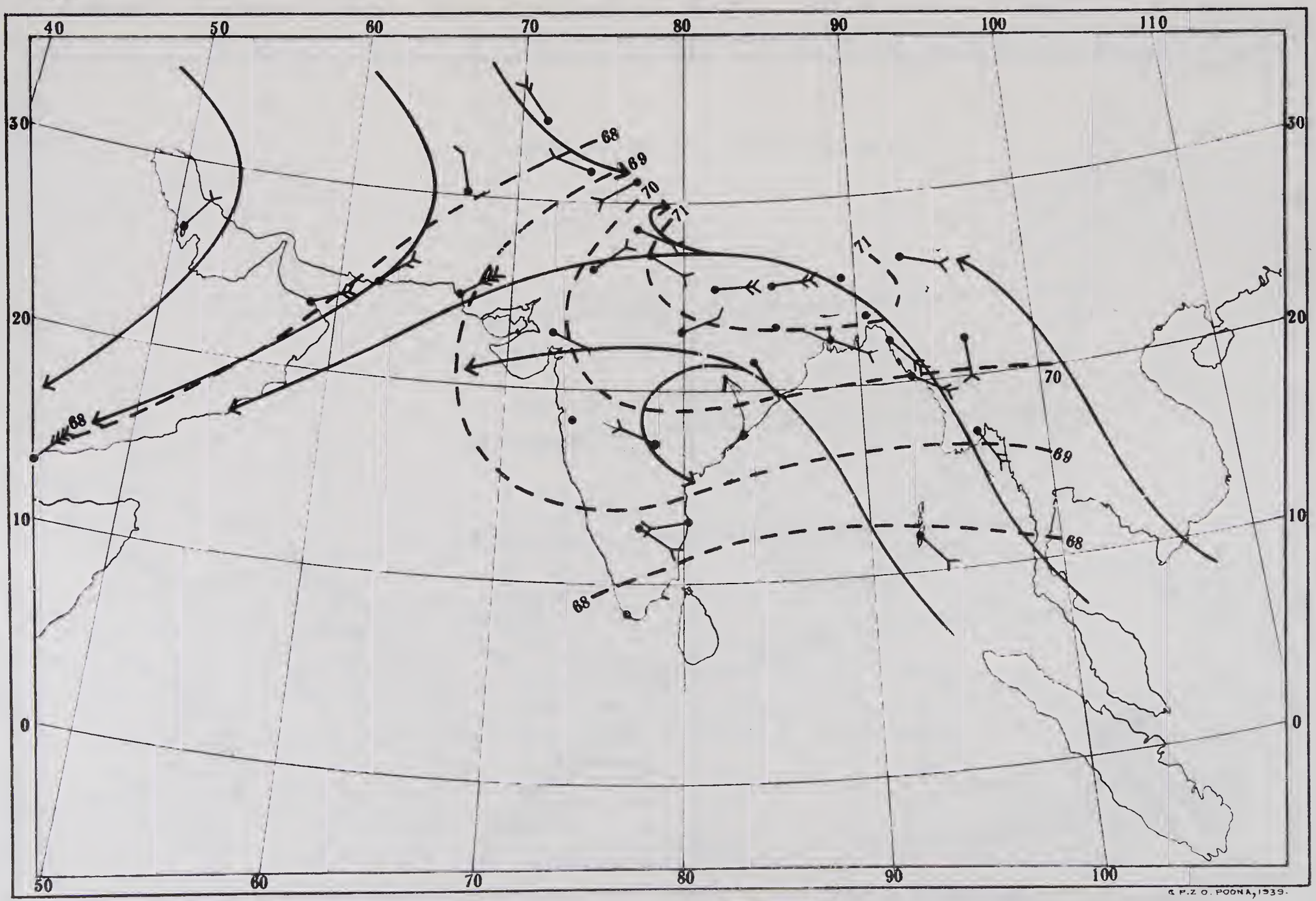
UPPER WINDS AND TEMPERATURES OVER INDIA —— JULY 2 KM.



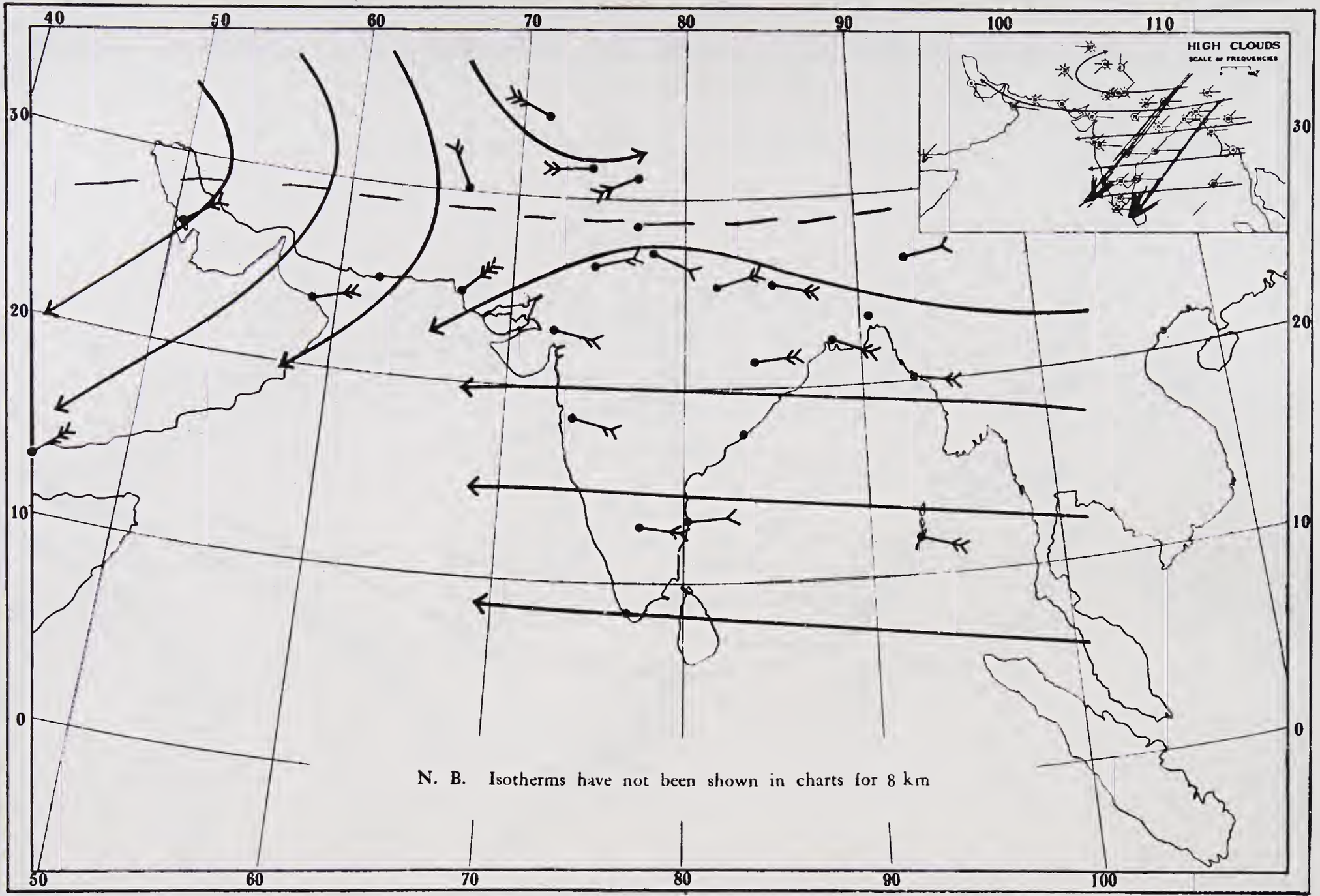
UPPER WINDS AND TEMPERATURES OVER INDIA —— JULY 3 KM.

UPPER WINDS AND TEMPERATURES OVER INDIA —— JULY 4 KM.

PLATE XLIII



UPPER WINDS AND TEMPERATURES OVER INDIA —— JULY 6 KM.

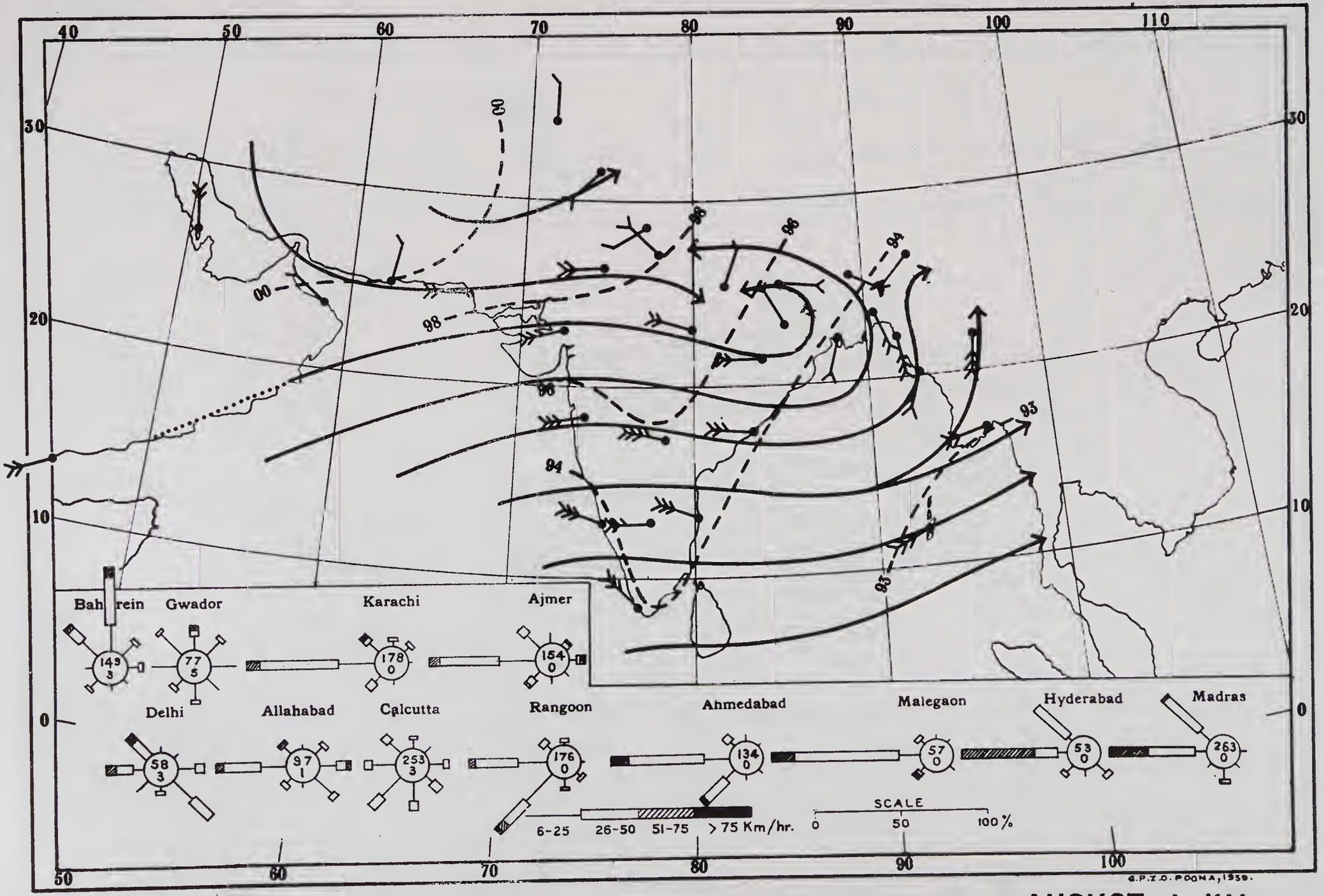


N. B. Isotherms have not been shown in charts for 8 km

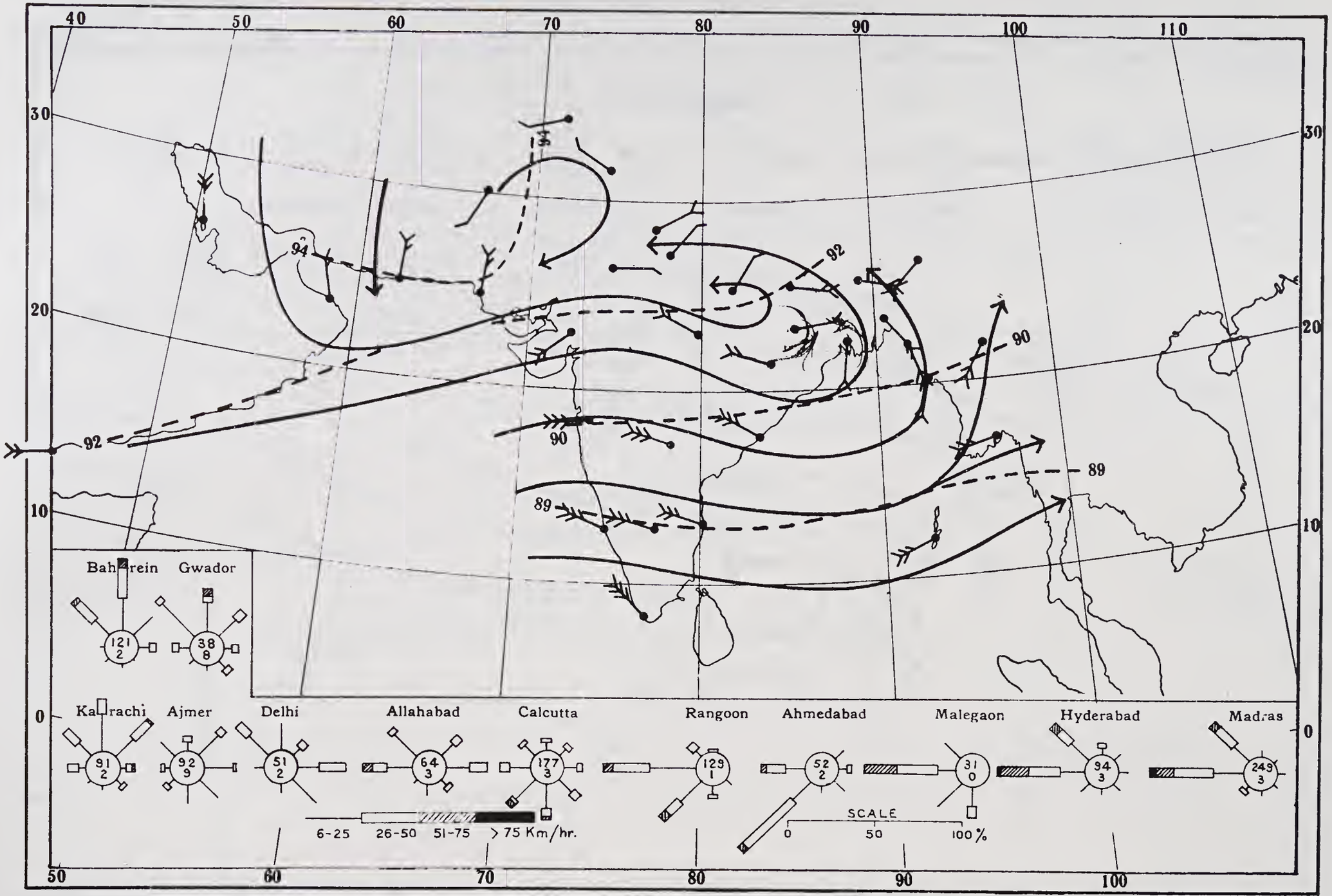
G. P. Z. D. POONA, 1939.

UPPER WINDS AND TEMPERATURES OVER INDIA —— JULY 8 KM.

PLATE XLV



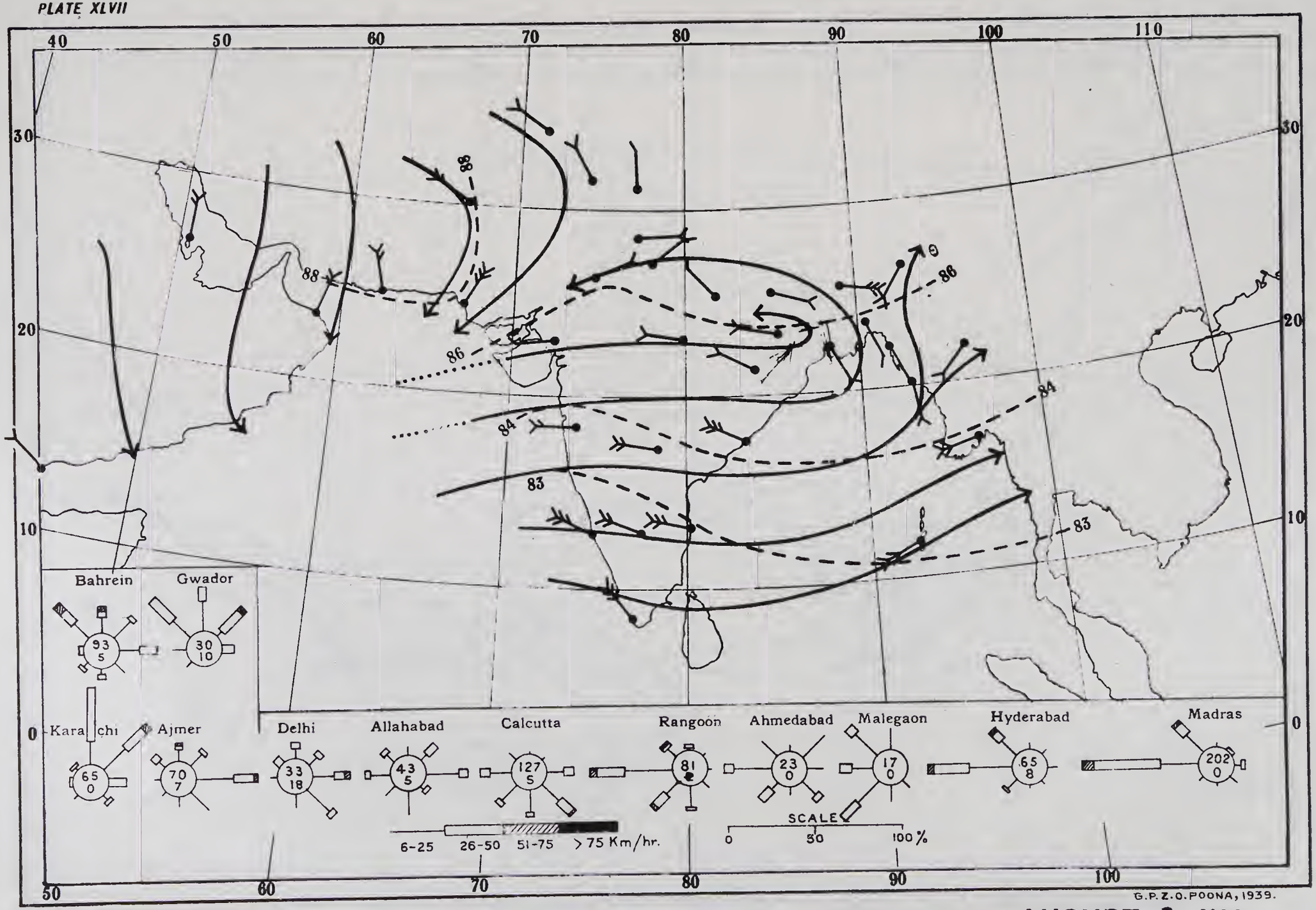
UPPER WINDS AND TEMPERATURES OVER INDIA —— AUGUST 1 KM.



G.P.Z O. POONA, 1939.

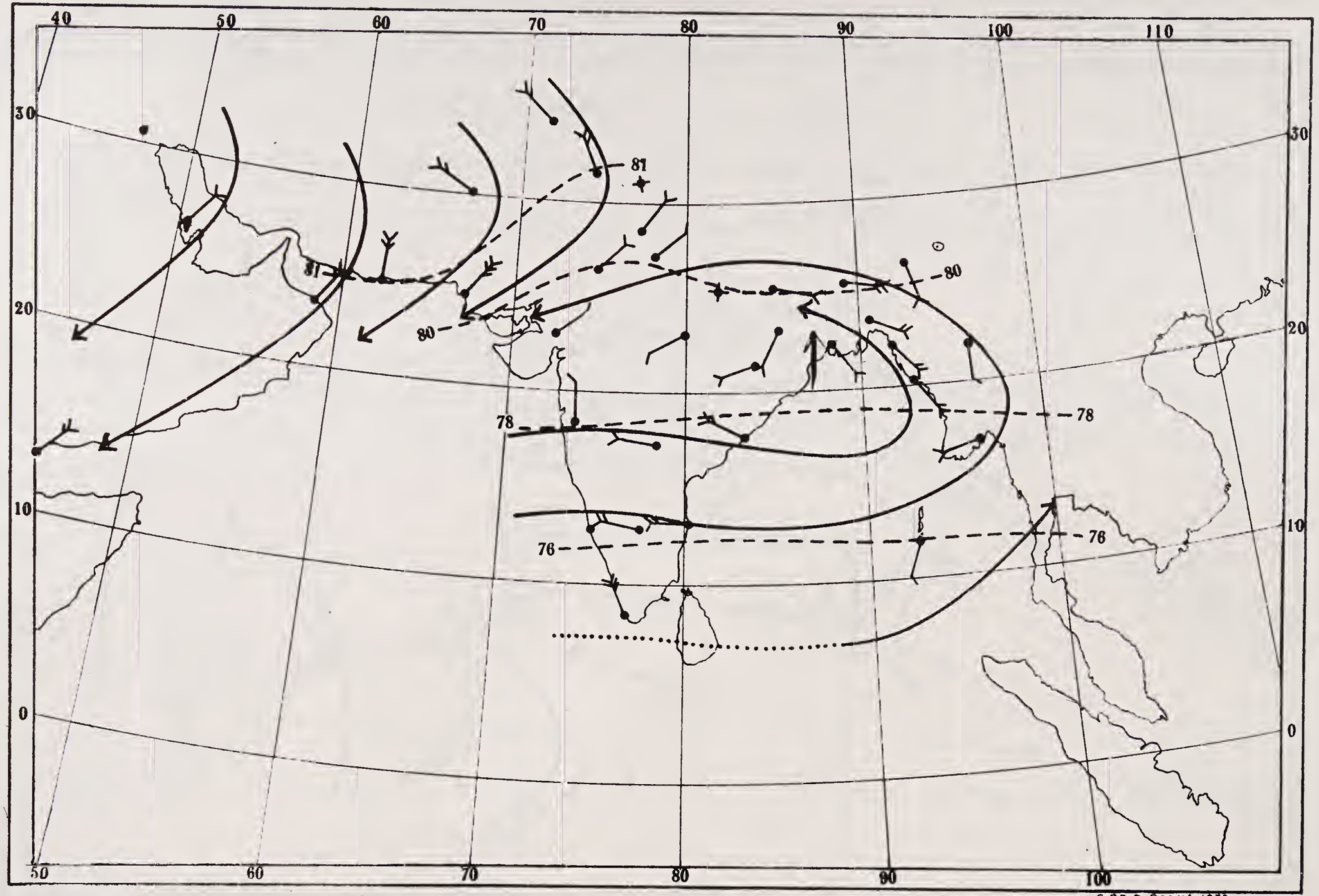
UPPER WINDS AND TEMPERATURES OVER INDIA —— AUGUST 2 KM.

PLATE XLVII



UPPER WINDS AND TEMPERATURES OVER INDIA —— AUGUST 3 KM.

PLATE XLVIII

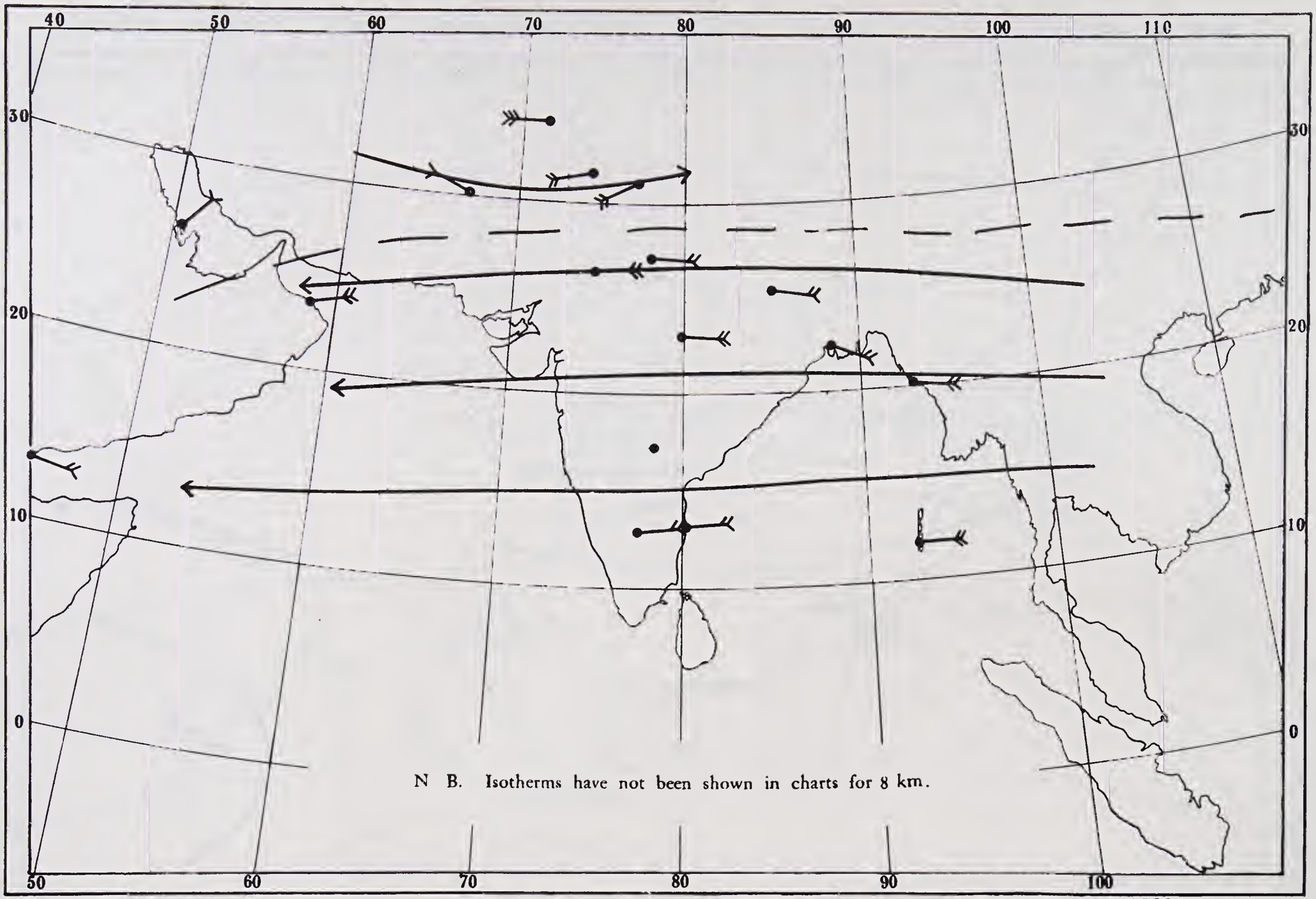


UPPER WINDS AND TEMPERATURES OVER INDIA —— AUGUST 4 KM.

PLATE XLIX

UPPER WINDS AND TEMPERATURES OVER INDIA —— AUGUST 6 KM.

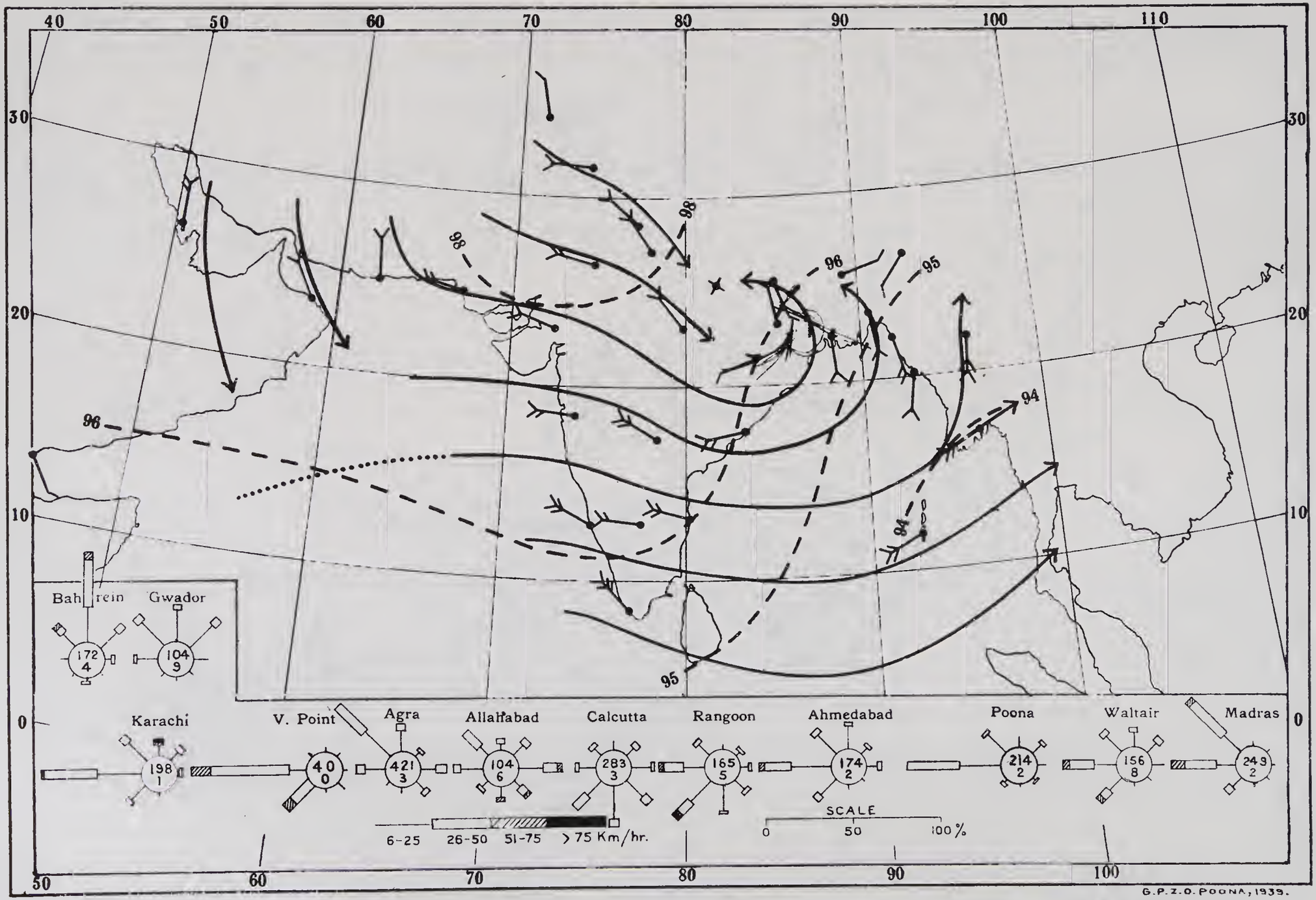
PLATE I



N B. Isotherms have not been shown in charts for 8 km.

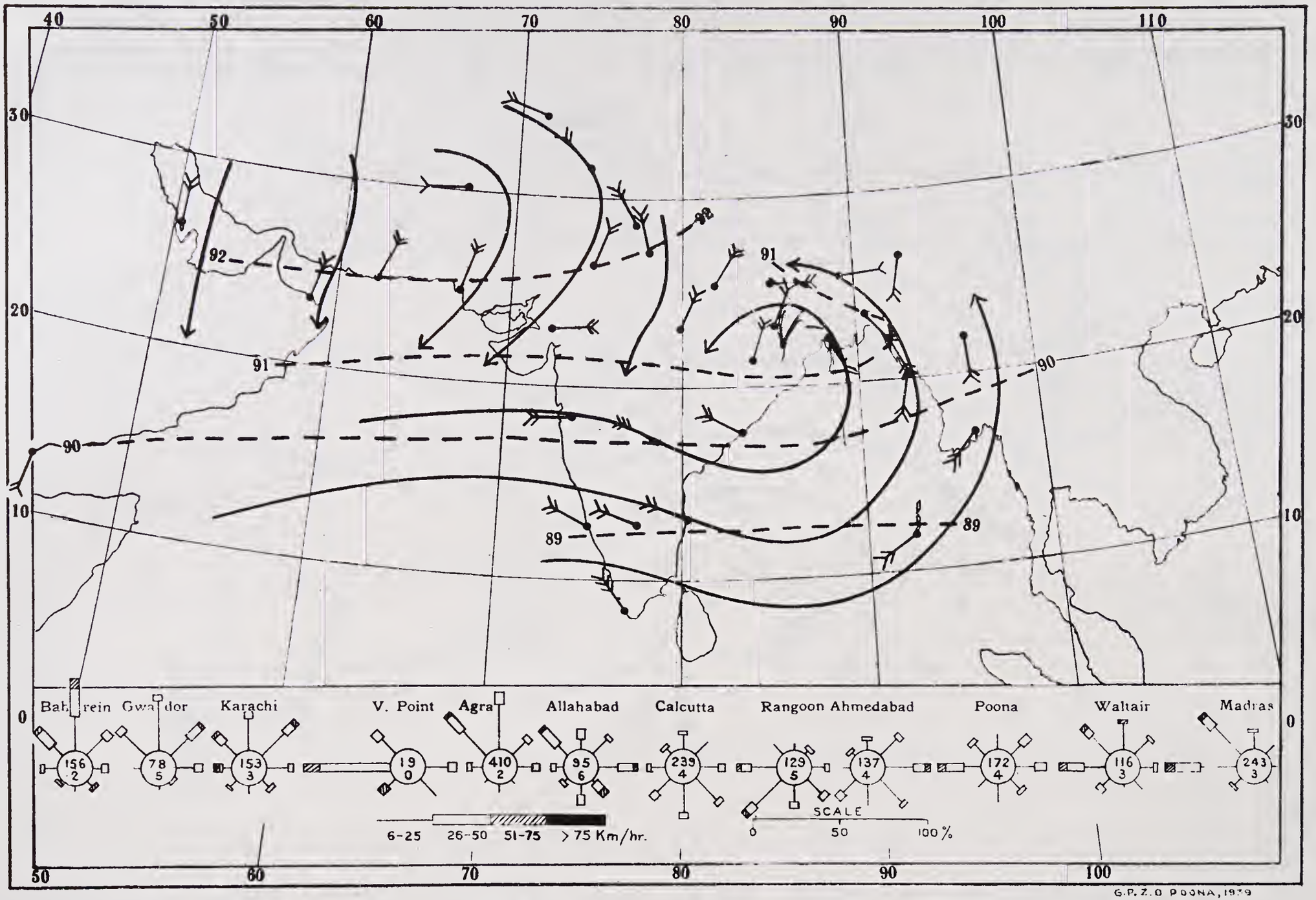
G.P.2.0. POONA, 1939.

UPPER WINDS AND TEMPERATURES OVER INDIA —— AUGUST 8 KM.



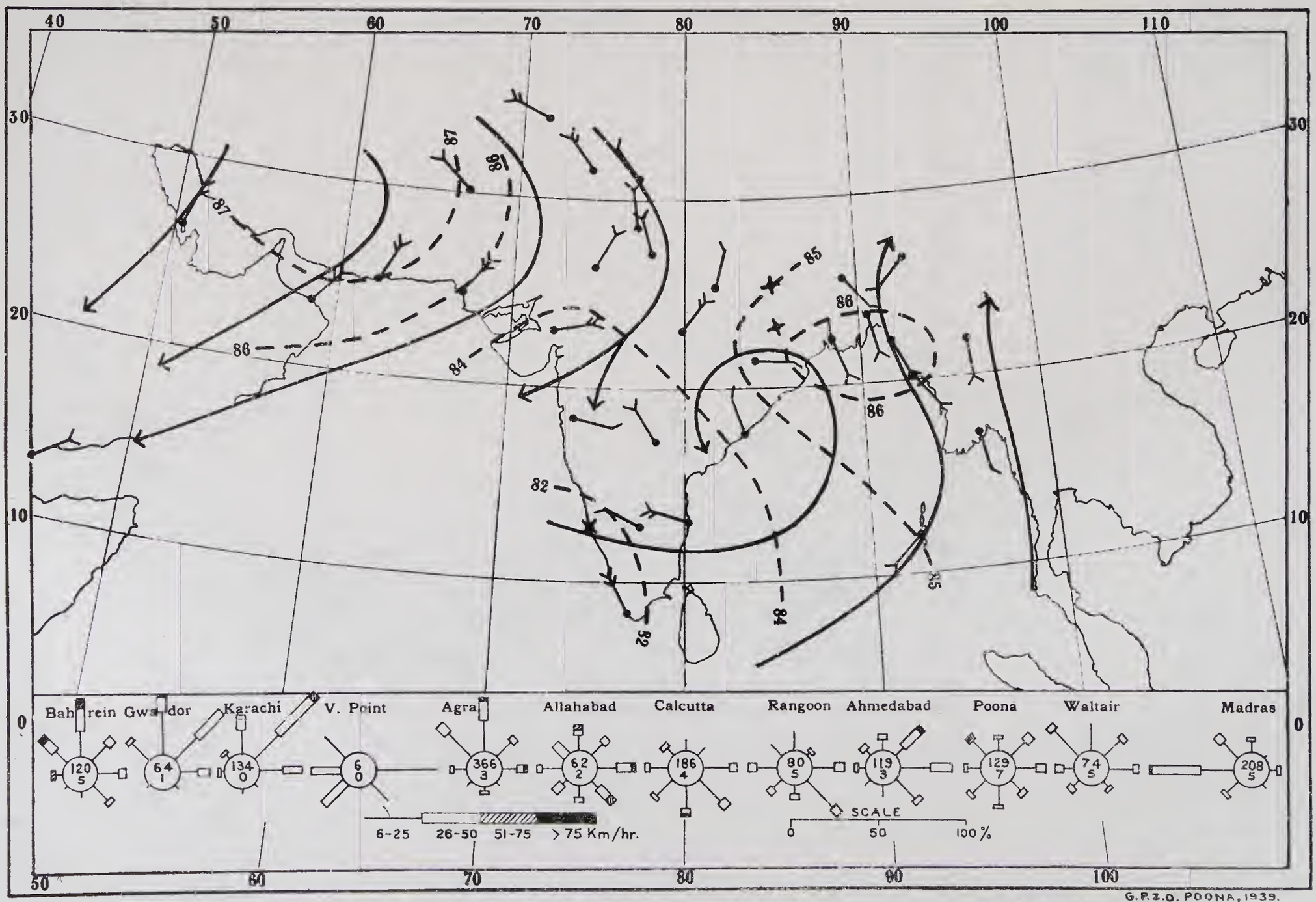
UPPER WINDS AND TEMPERATURES OVER INDIA —— SEPTEMBER 1 KM.

PLATE LII



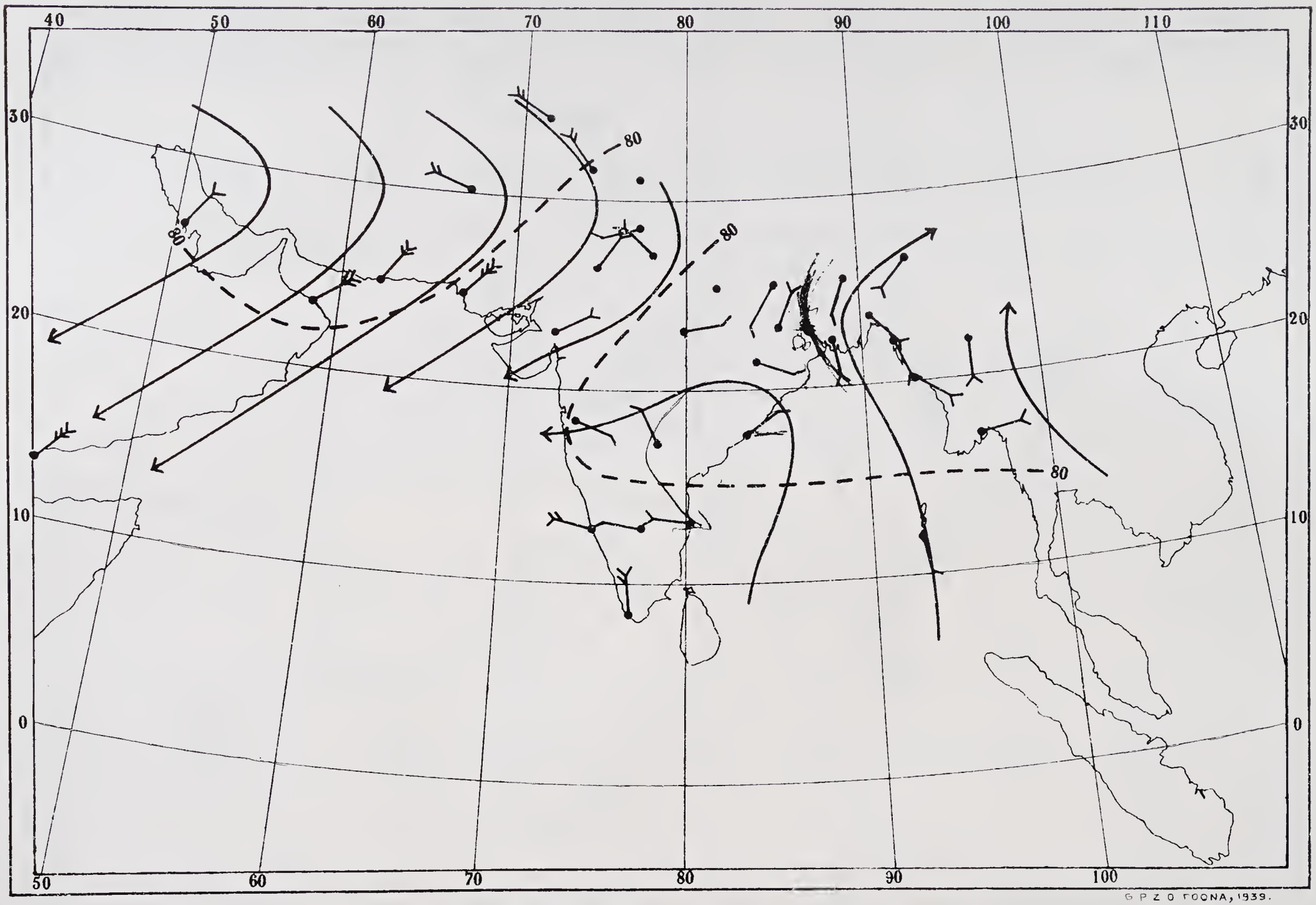
G.P.Z.O POONA, 1939

UPPER WINDS AND TEMPERATURES OVER INDIA —— SEPTEMBER 2 KM.



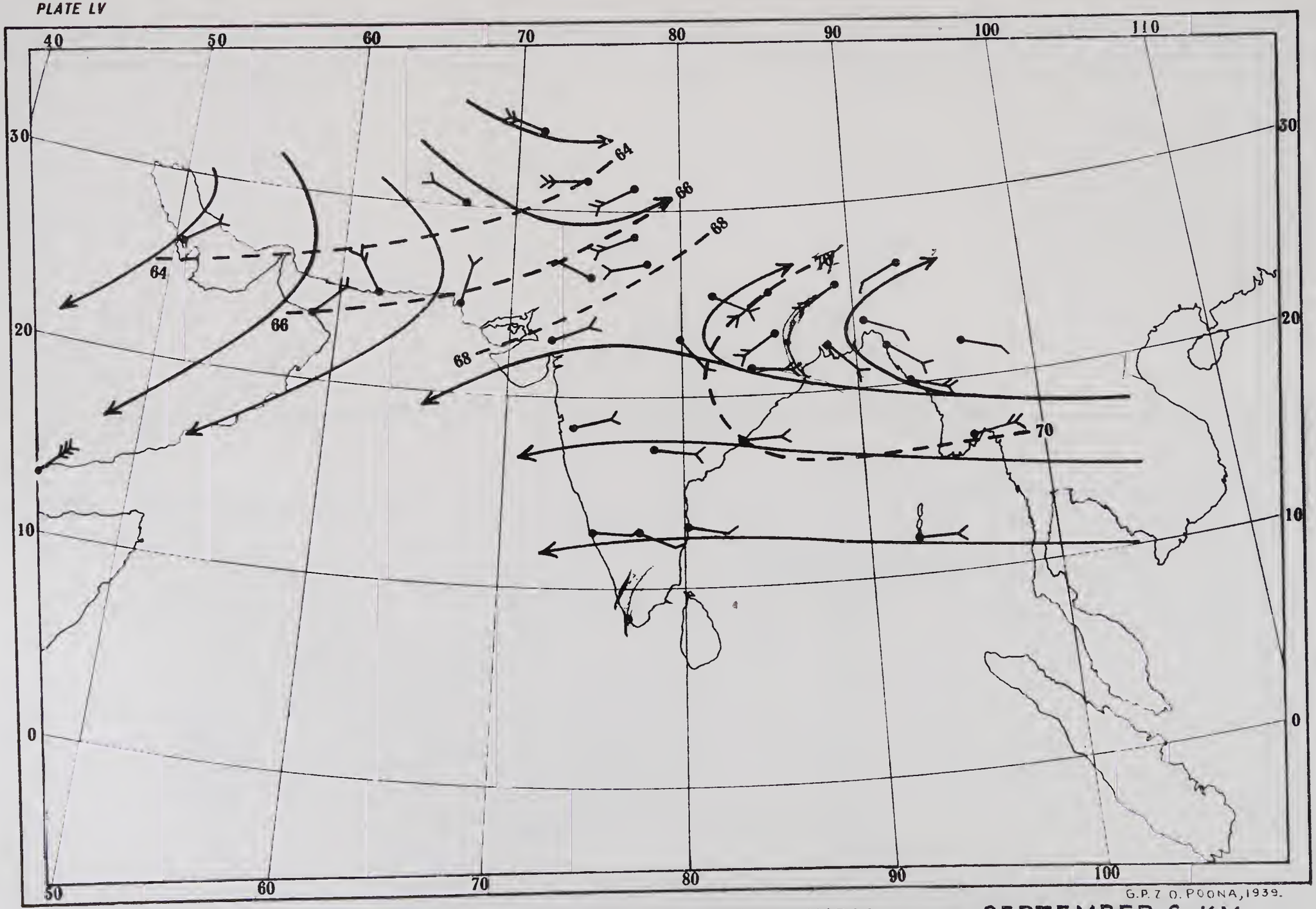
UPPER WINDS AND TEMPERATURES OVER INDIA —— SEPTEMBER 3 KM.

PLATE LIV



G P Z O POONA, 1939.

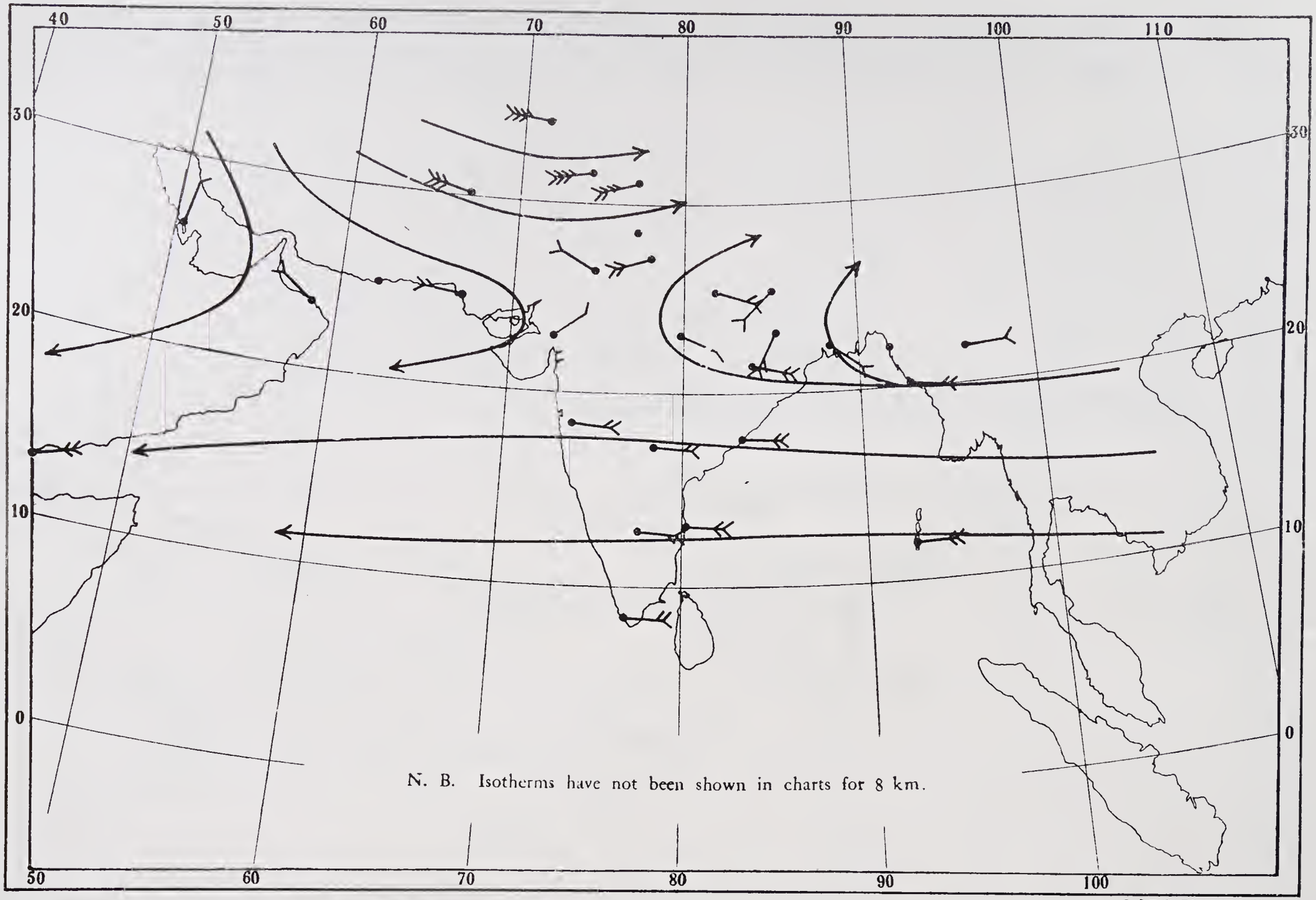
UPPER WINDS AND TEMPERATURES OVER INDIA —— SEPTEMBER 4 KM.



G.P.Z O. POONA, 1939.

UPPER WINDS AND TEMPERATURES OVER INDIA ——— SEPTEMBER 6 KM.

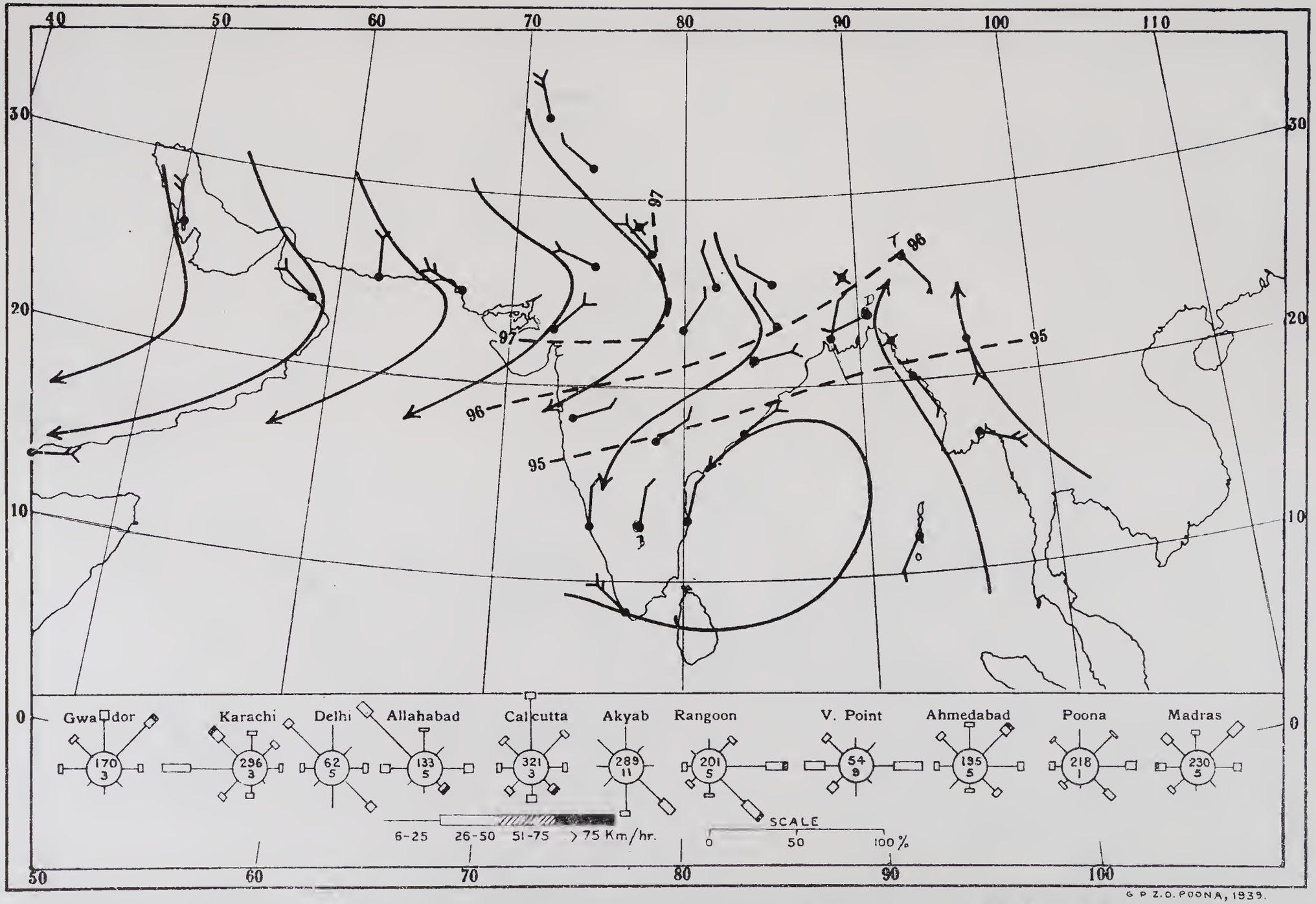
PLATE LVI



N. B. Isotherms have not been shown in charts for 8 km.

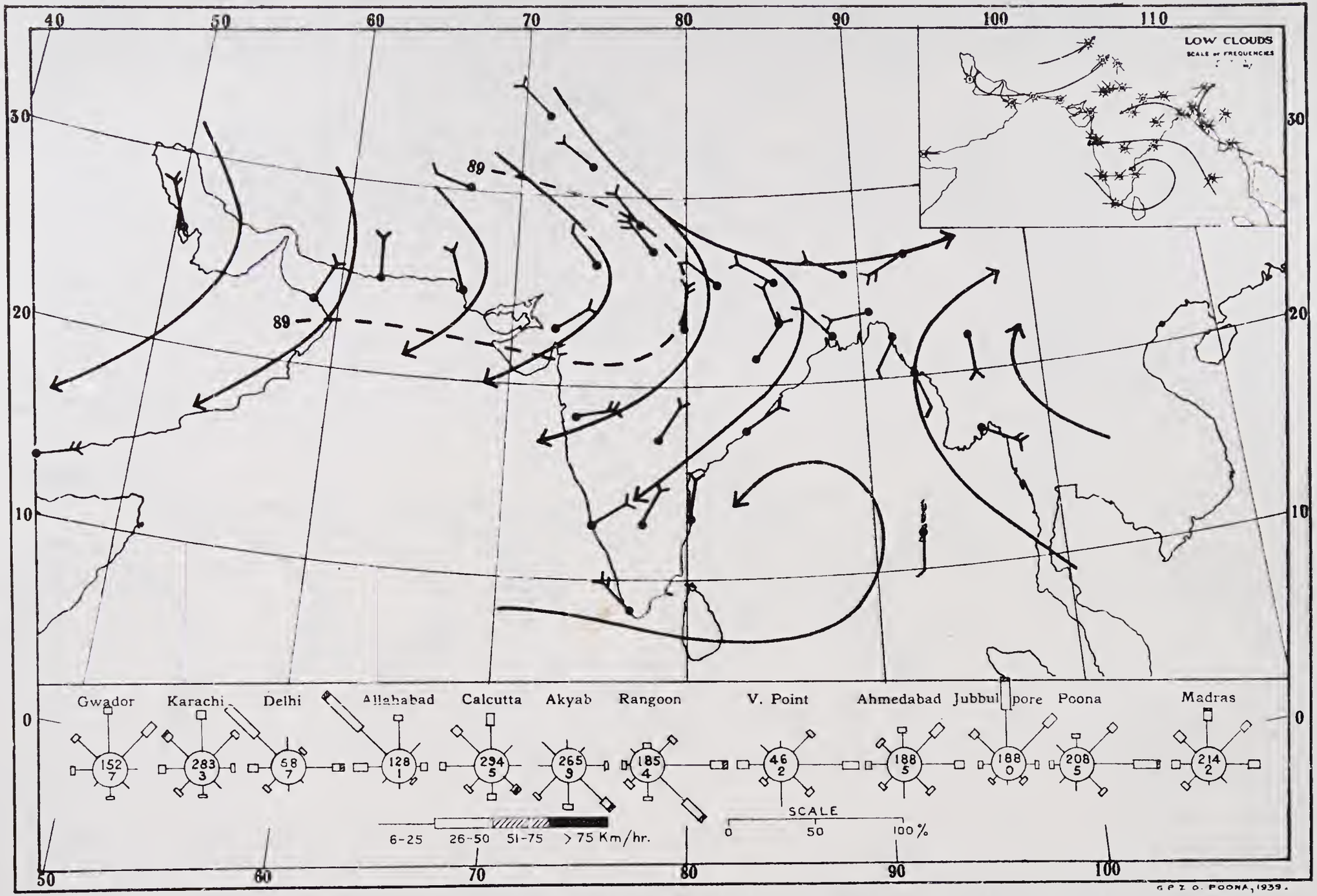
G P.Z.O. POONA, 1939.

UPPER WINDS AND TEMPERATURES OVER INDIA —— SEPTEMBER 8 KM.

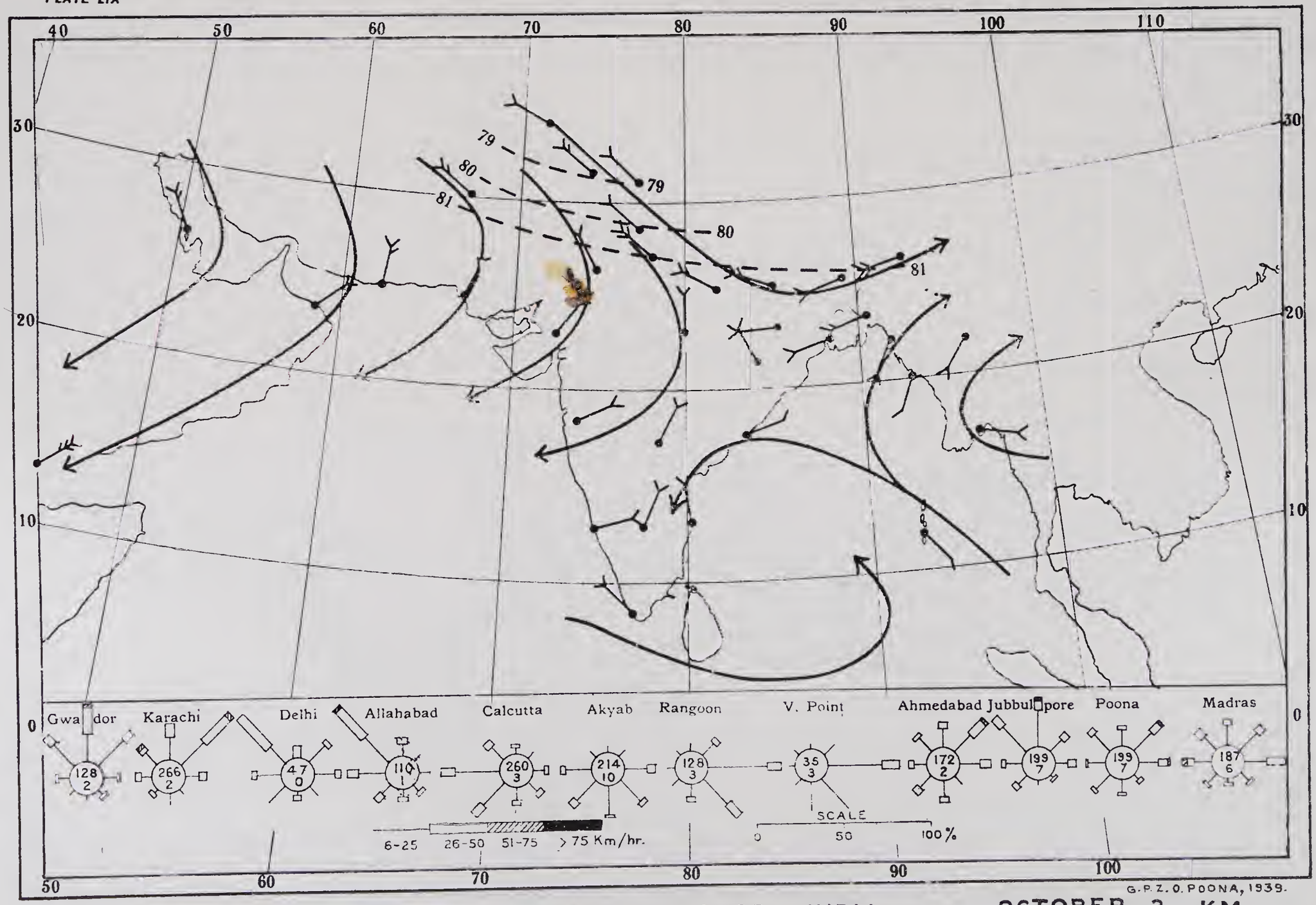


G P Z.O. POONA, 1939.

UPPER WINDS AND TEMPERATURES OVER INDIA —— OCTOBER 1 KM.

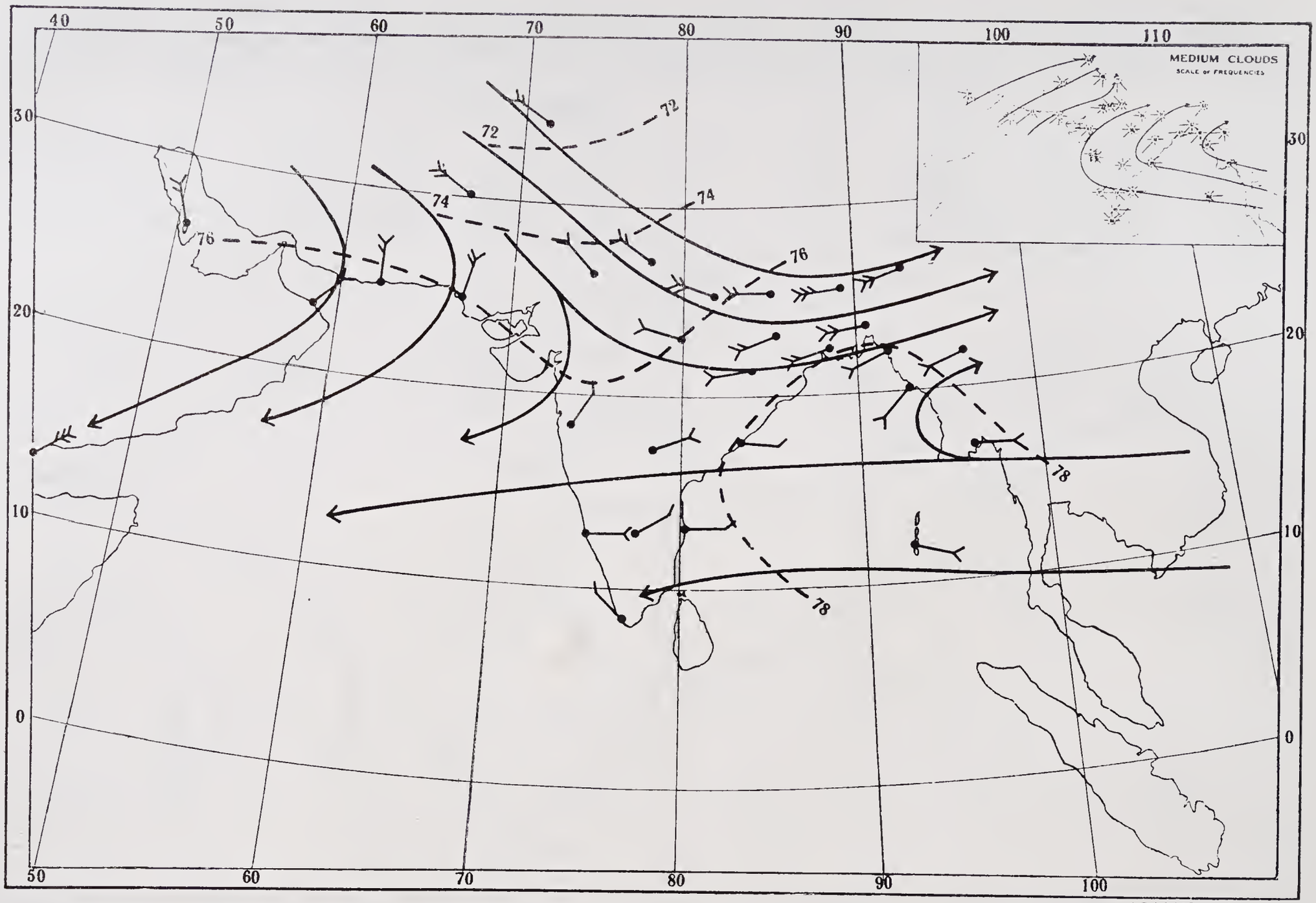


UPPER WINDS AND TEMPERATURES OVER INDIA —— OCTOBER 2 KM.



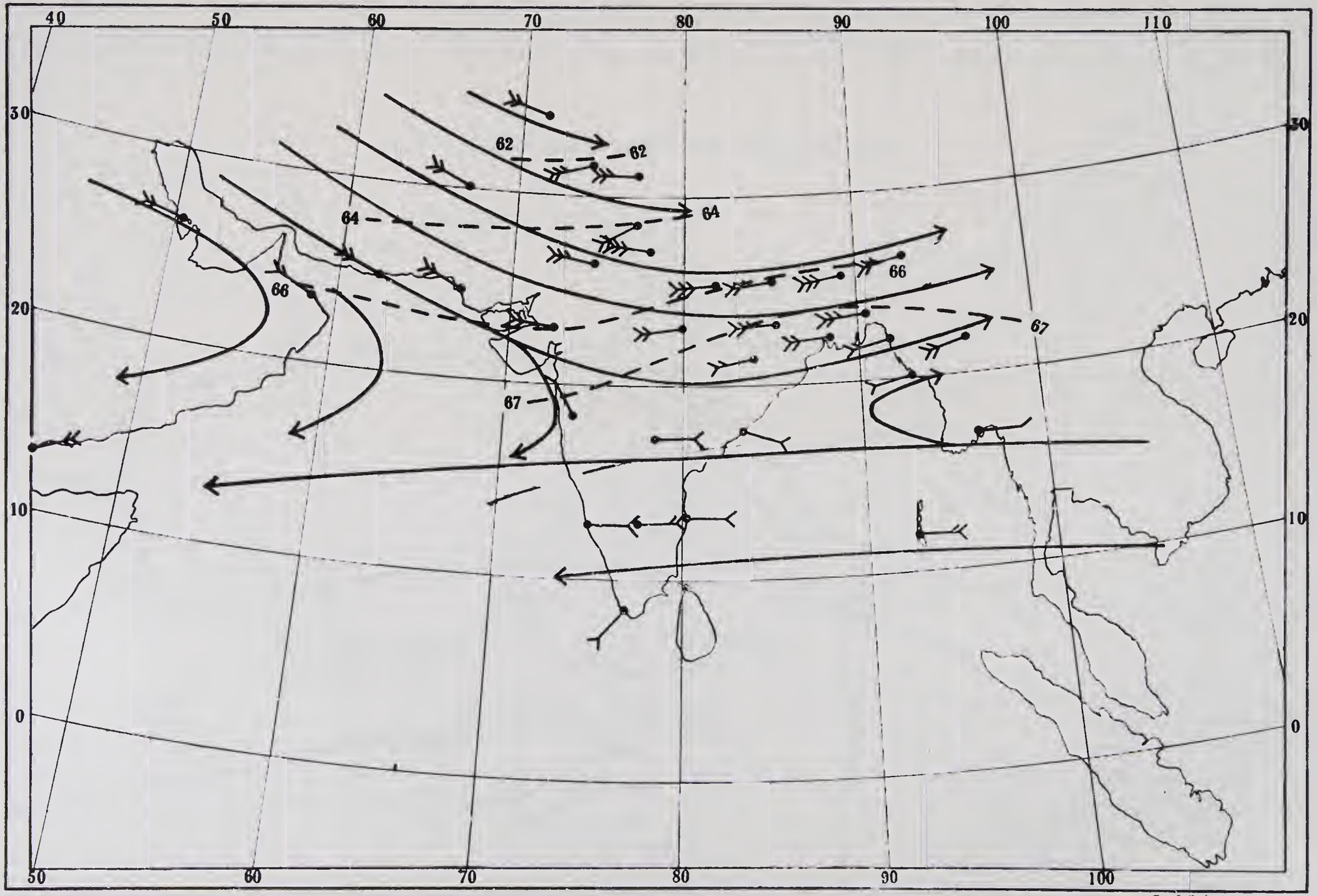
UPPER WINDS AND TEMPERATURES OVER INDIA —— OCTOBER 3 KM.

PLATE LX

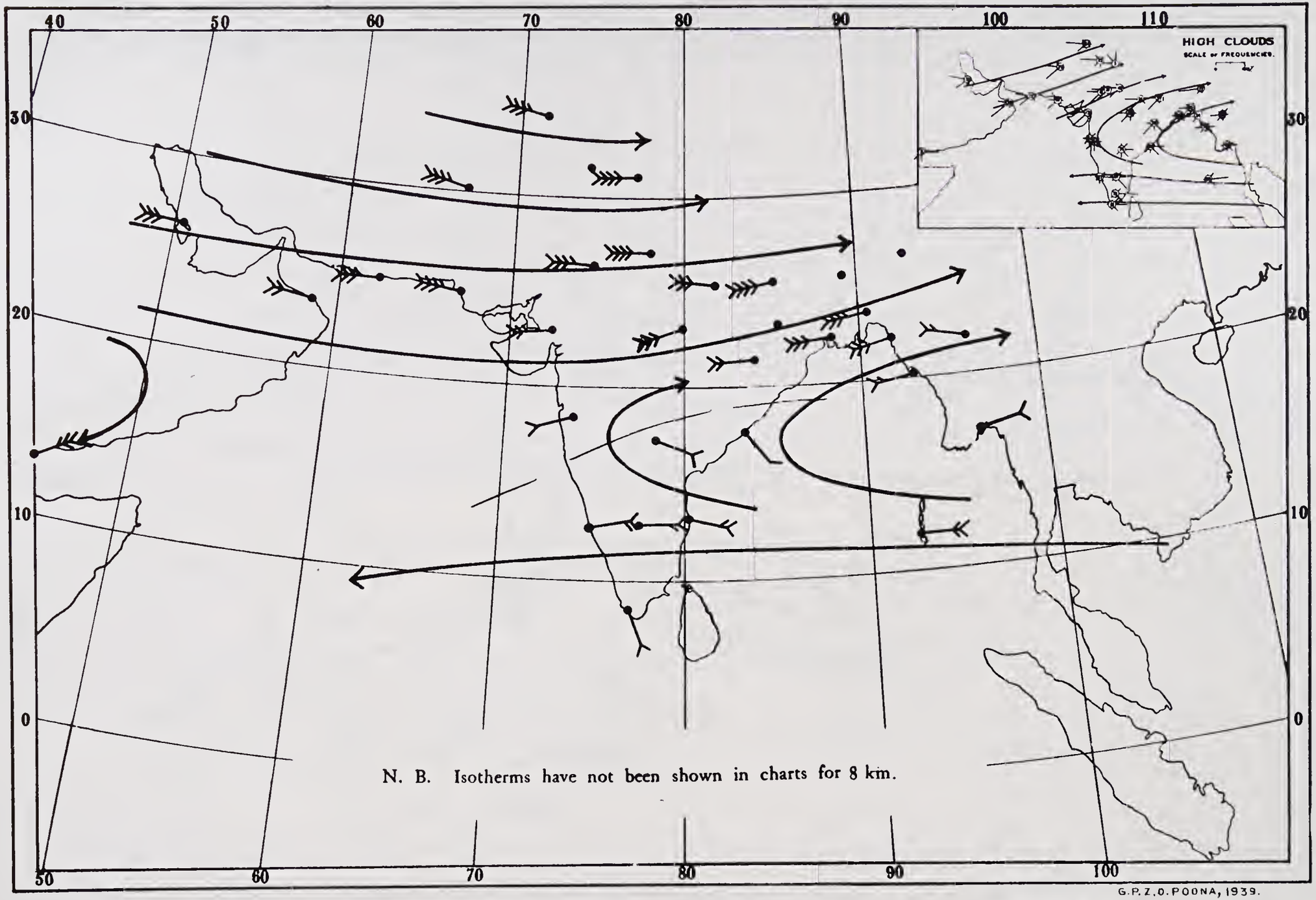


UPPER WINDS AND TEMPERATURES OVER INDIA —— OCTOBER 4 KM.

PLATE LXI

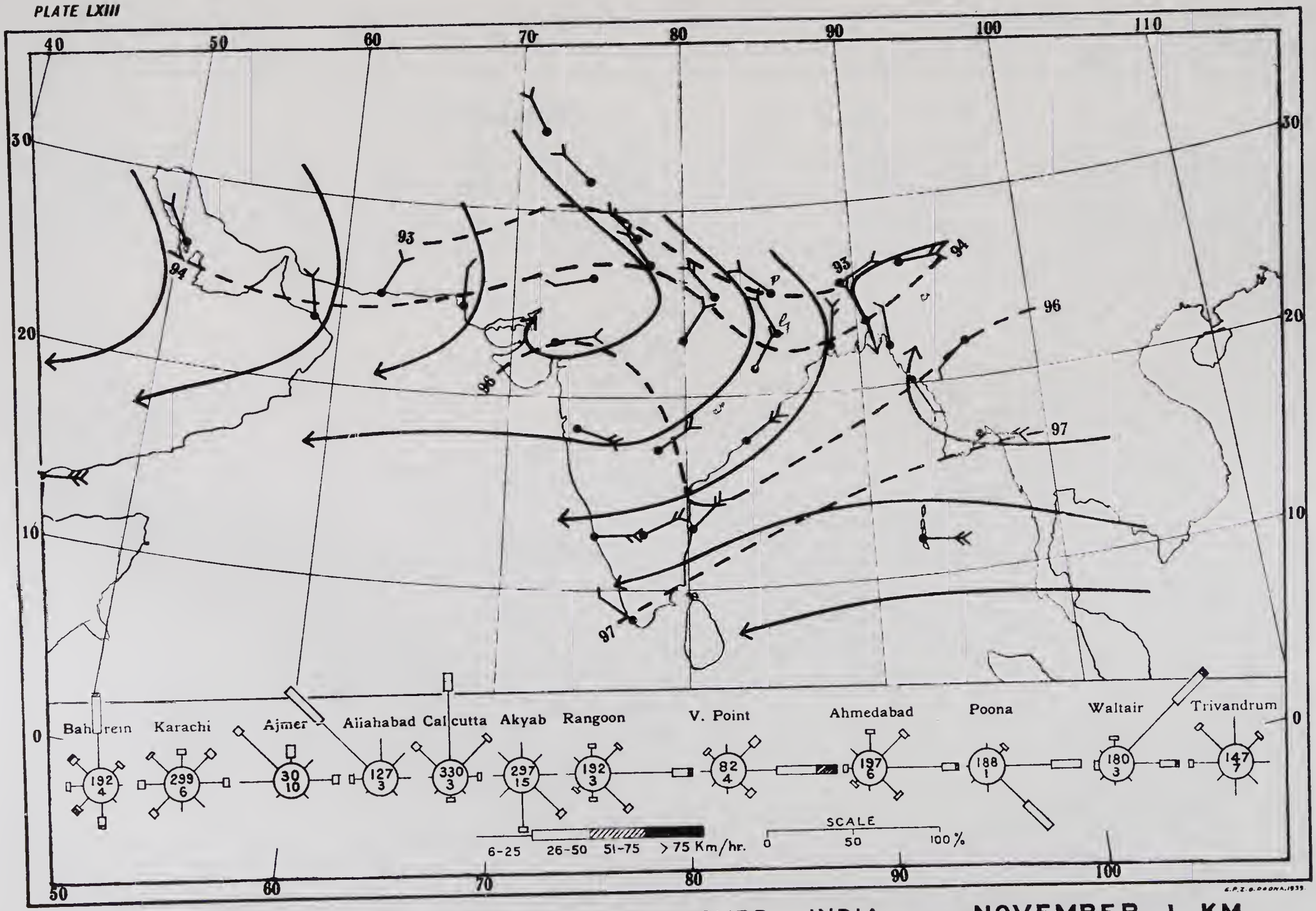


UPPER WINDS AND TEMPERATURES OVER INDIA —— OCTOBER 6 KM.

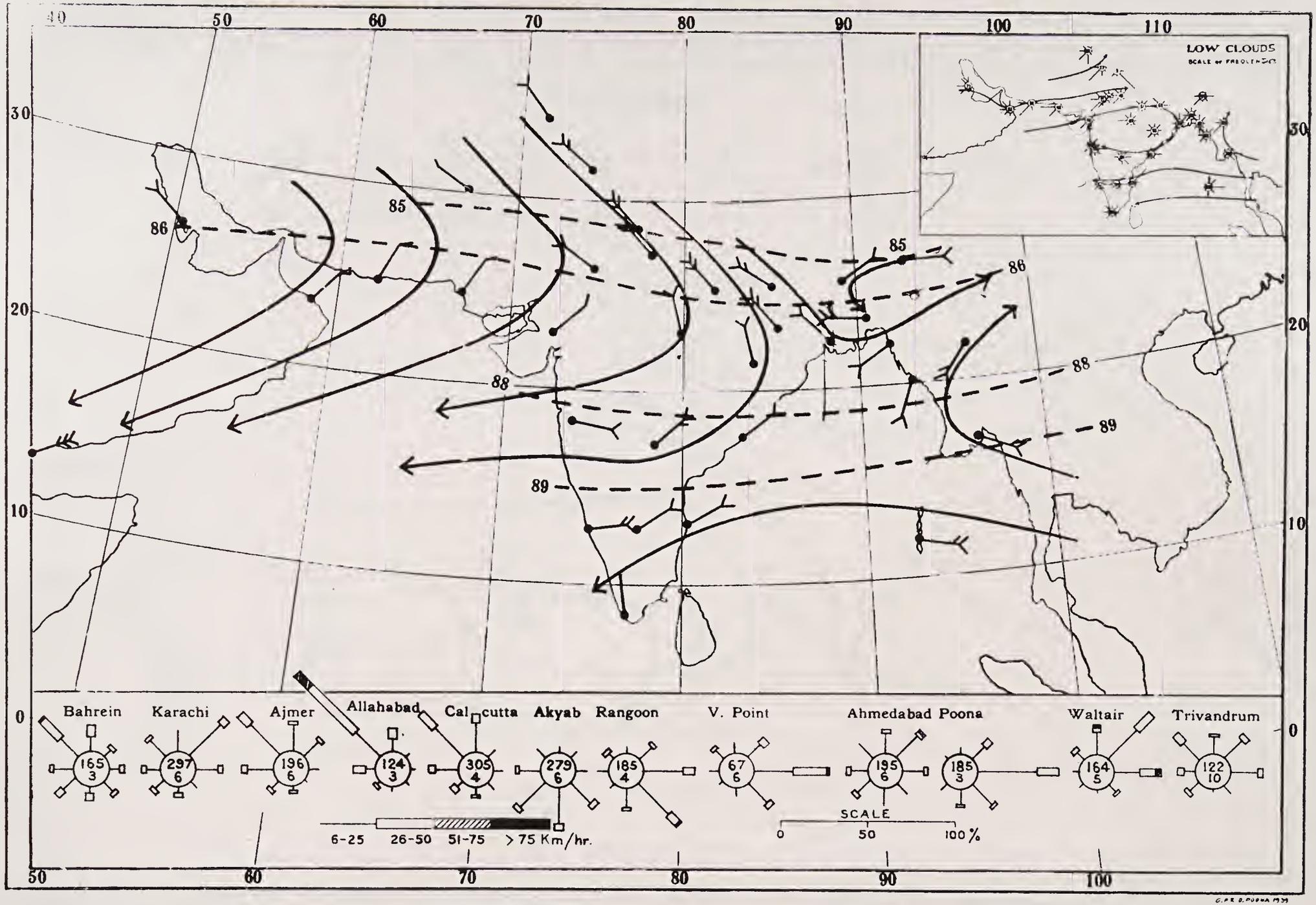


N. B. Isotherms have not been shown in charts for 8 km.

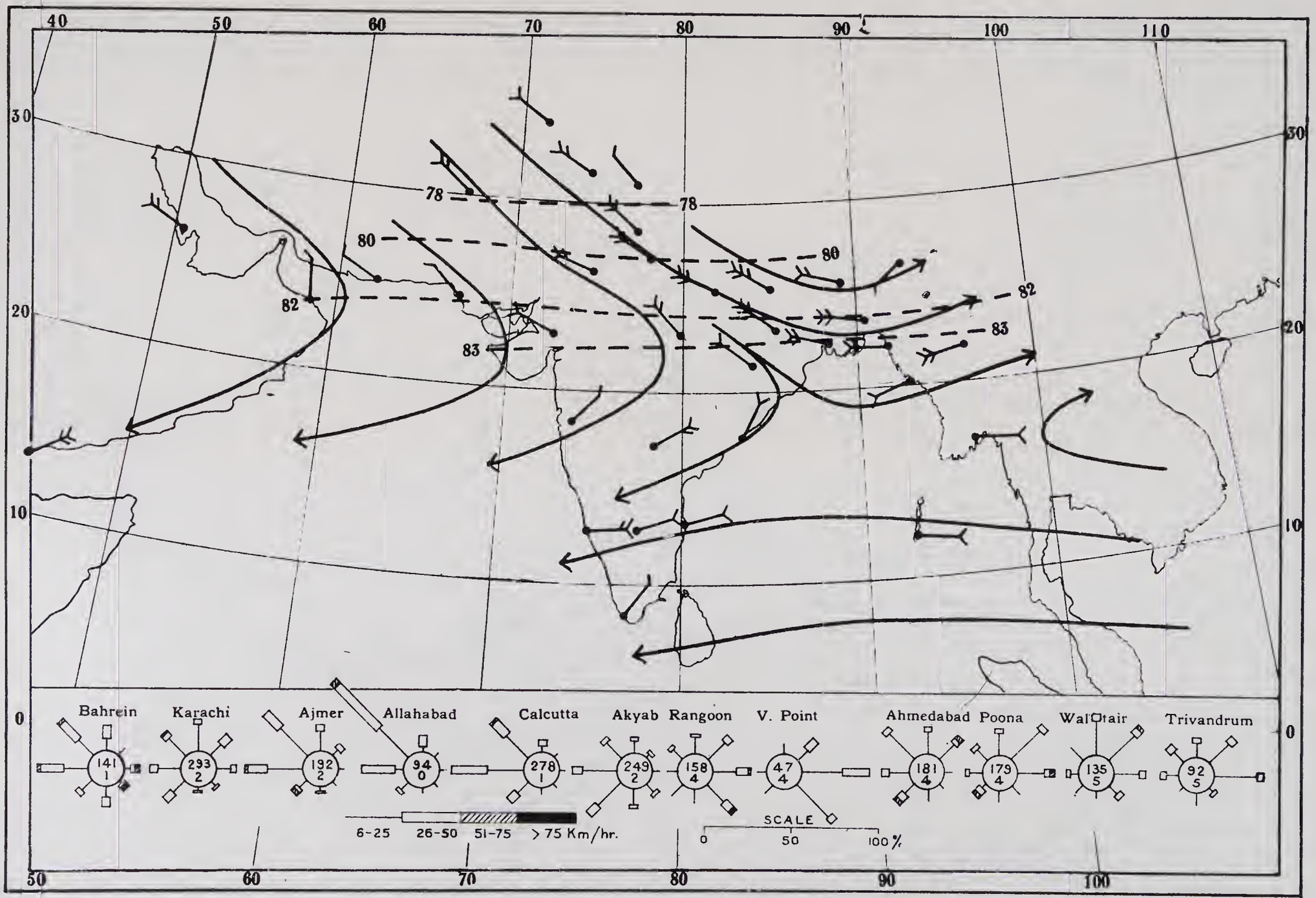
UPPER WINDS AND TEMPERATURES OVER INDIA —— OCTOBER 8 KM.



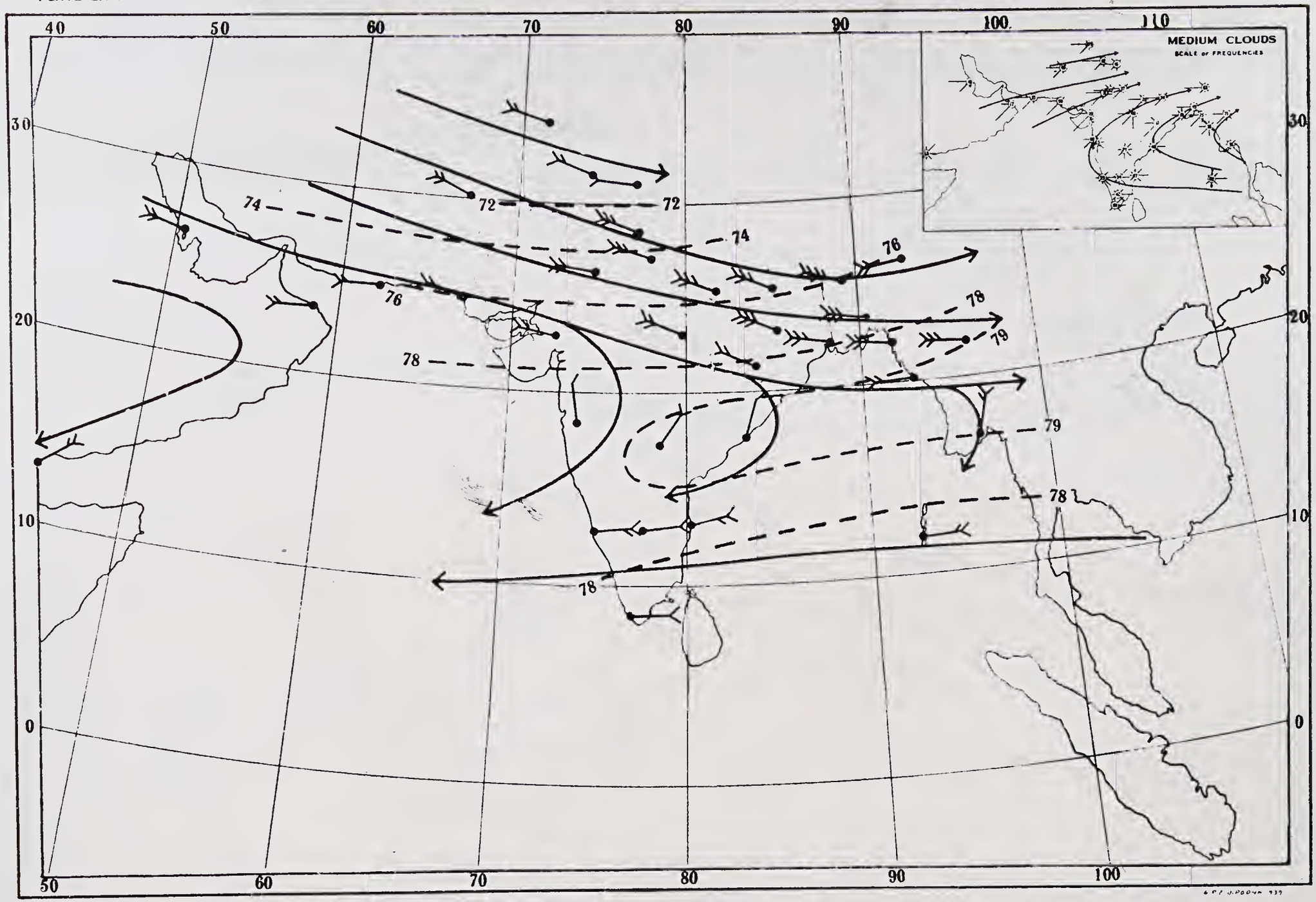
UPPER WINDS AND TEMPERATURES OVER INDIA ——NOVEMBER 1 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA ——NOVEMBER 2 KM

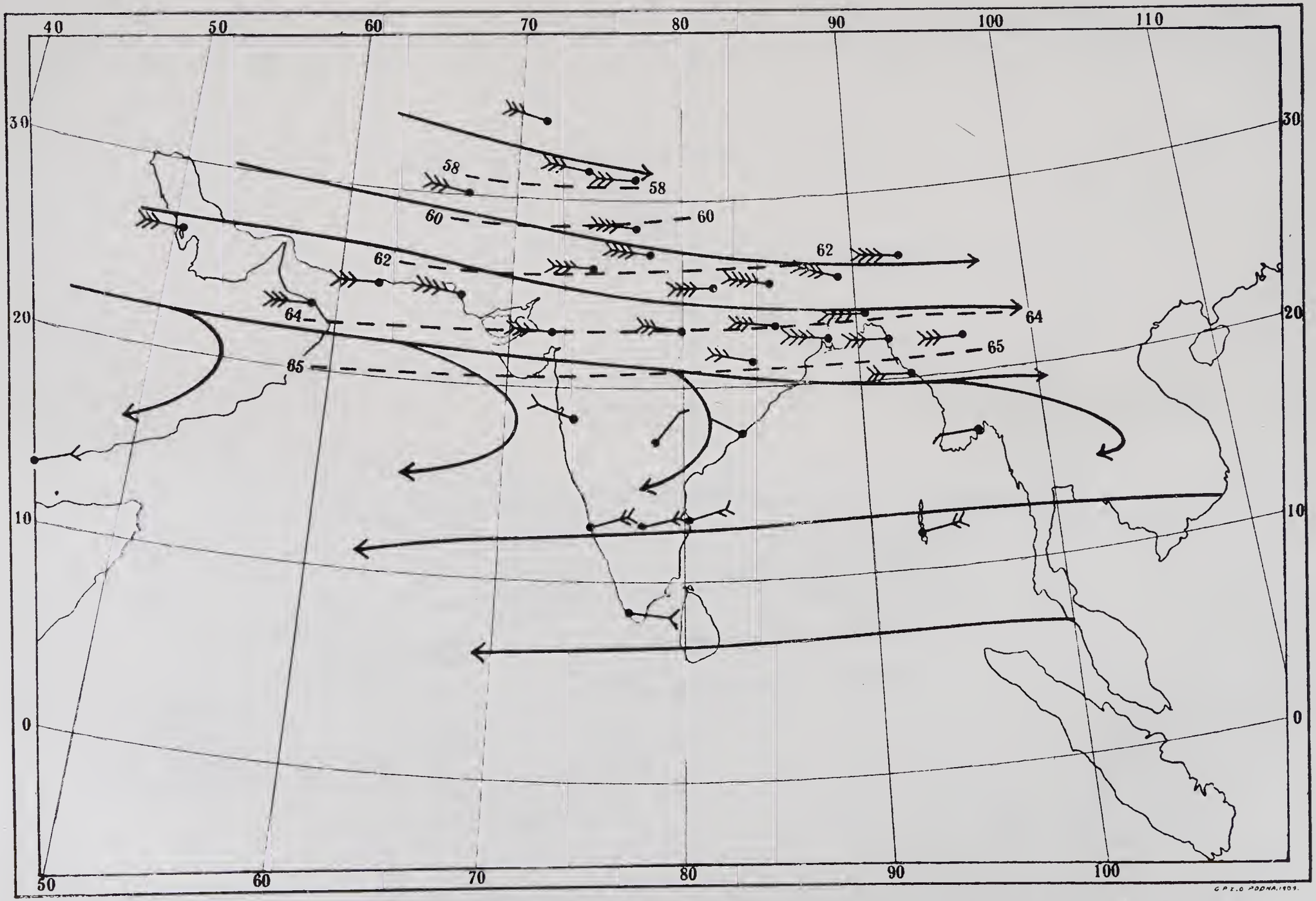


UPPER WINDS AND TEMPERATURES OVER INDIA ——NOVEMBER 3 KM.

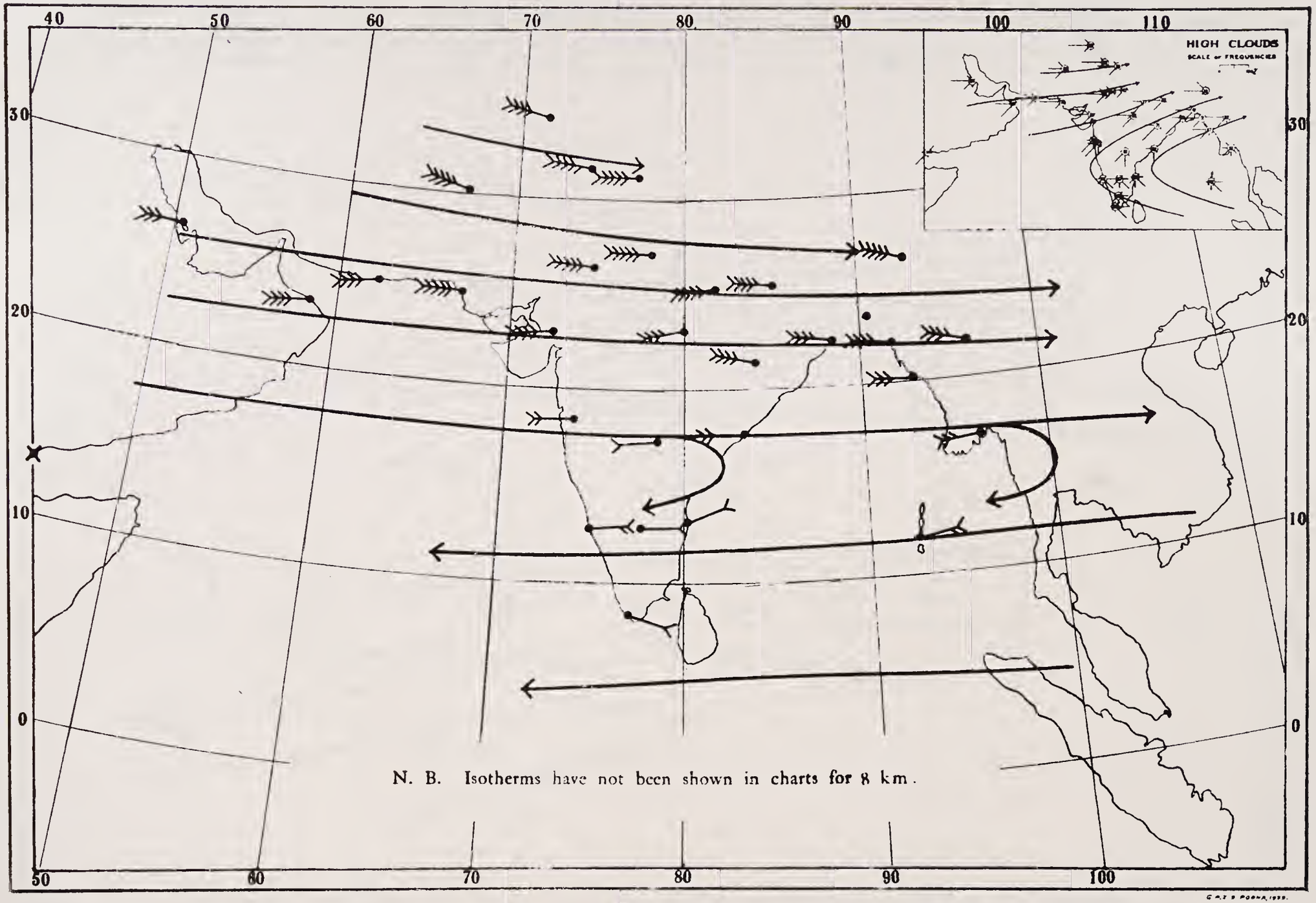


UPPER WINDS AND TEMPERATURES OVER INDIA ——— NOVEMBER 4 KM.

PLATE LXVII

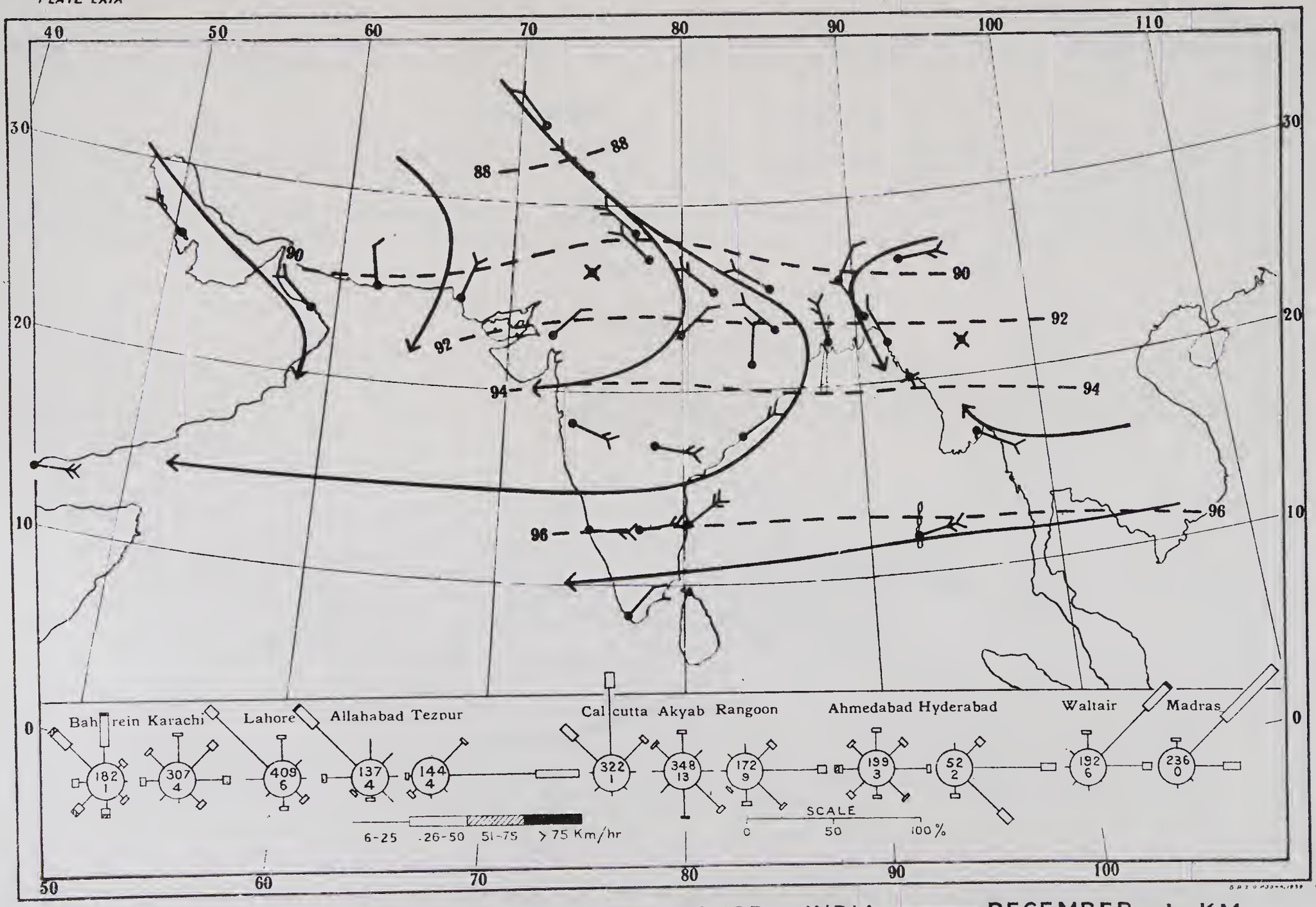


UPPER WINDS AND TEMPERATURES OVER INDIA ——NOVEMBER 6 KM.

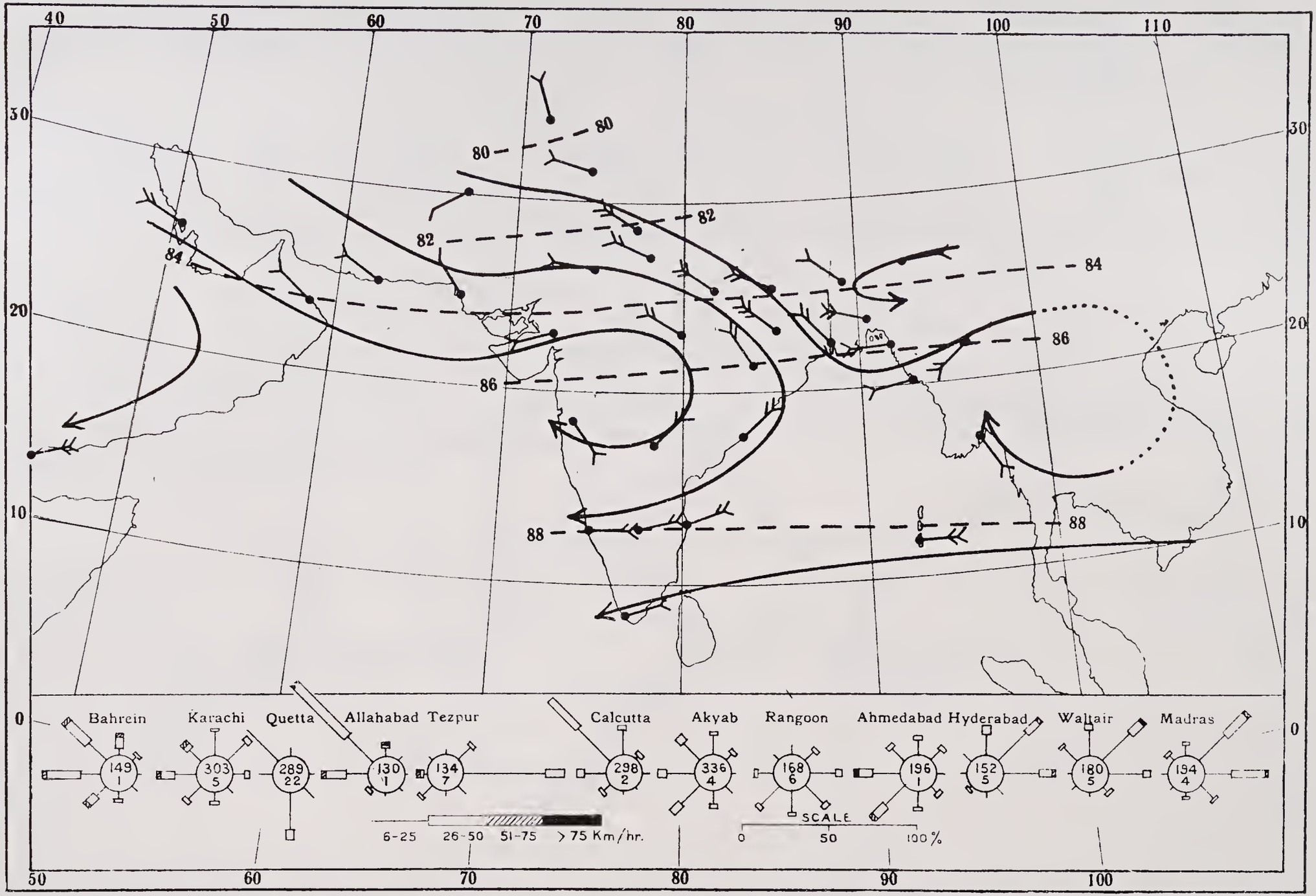


N. B. Isotherms have not been shown in charts for 8 km.

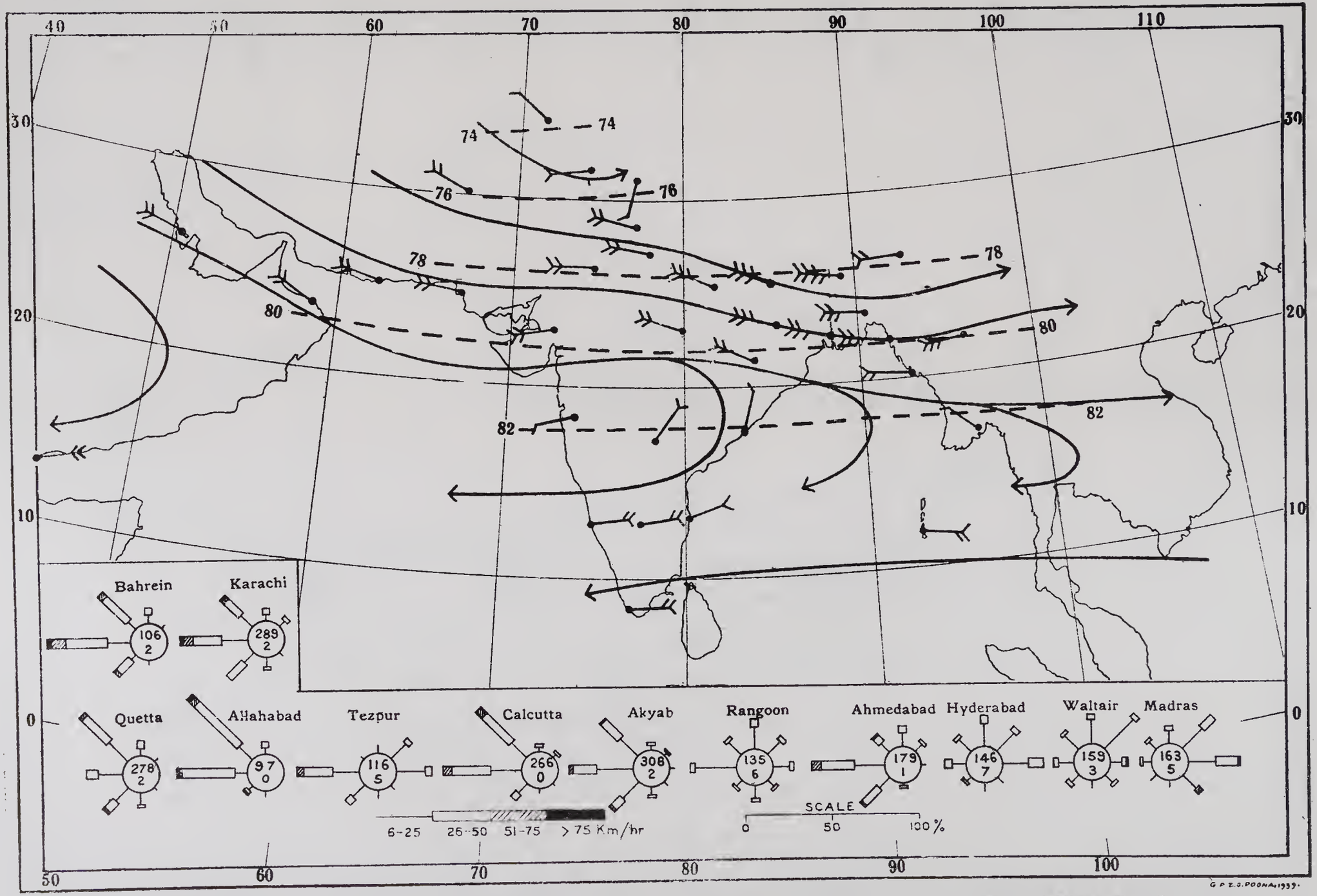
UPPER WINDS AND TEMPERATURES OVER INDIA ——NOVEMBER 8 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— DECEMBER 1 KM.

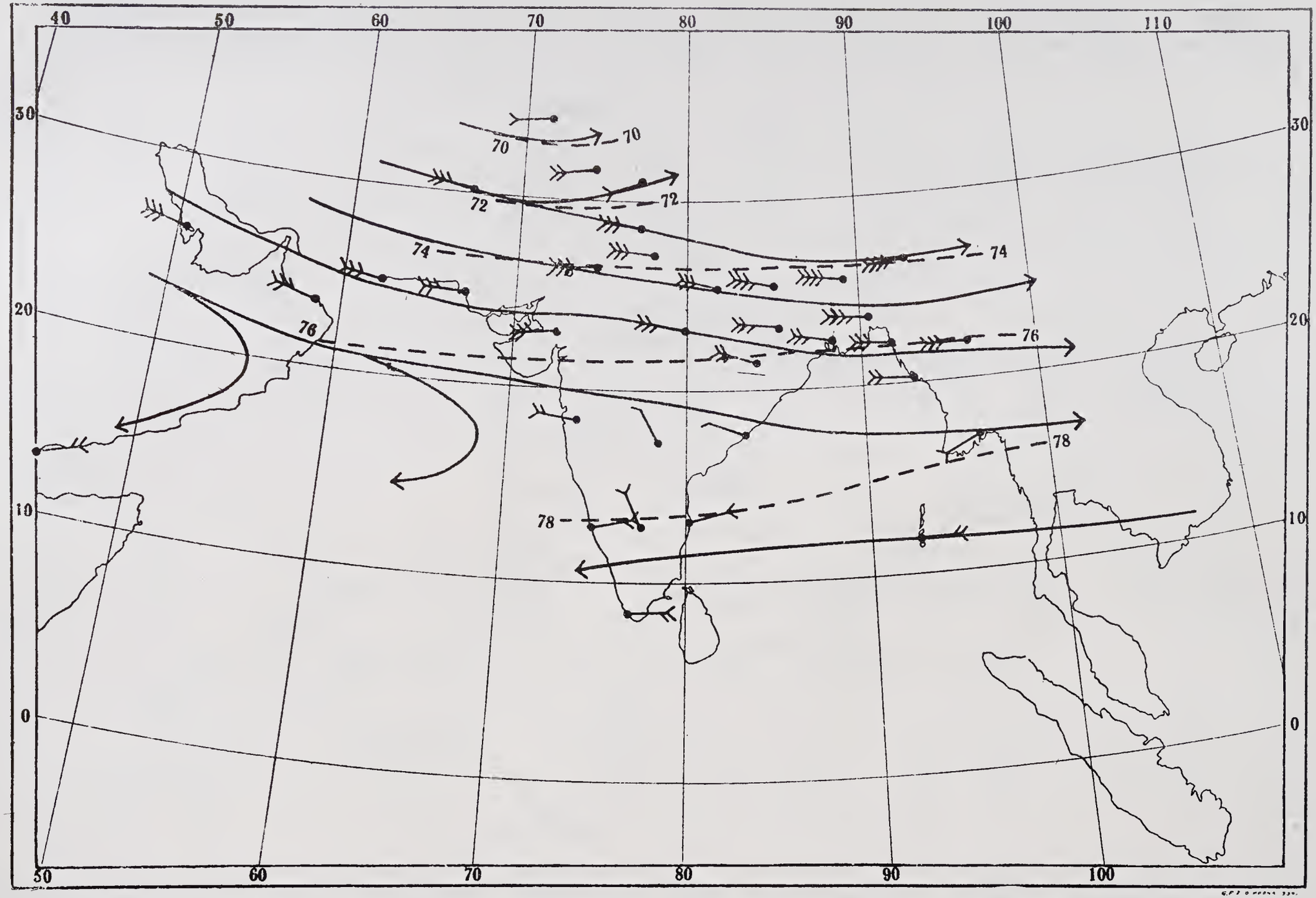


UPPER WINDS AND TEMPERATURES OVER INDIA ——— DECEMBER 2 KM.

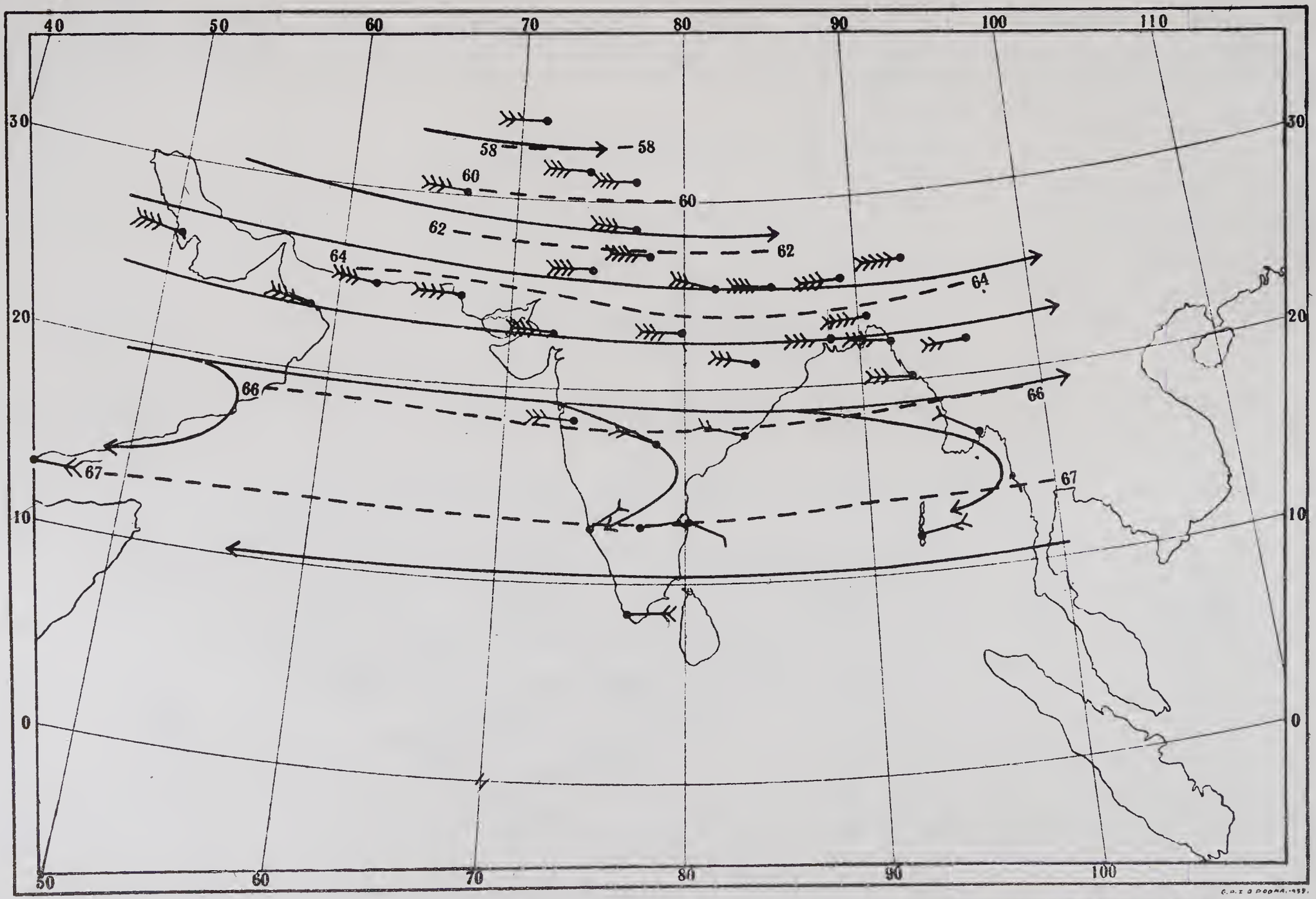


UPPER WINDS AND TEMPERATURES OVER INDIA —— DECEMBER 3 KM.

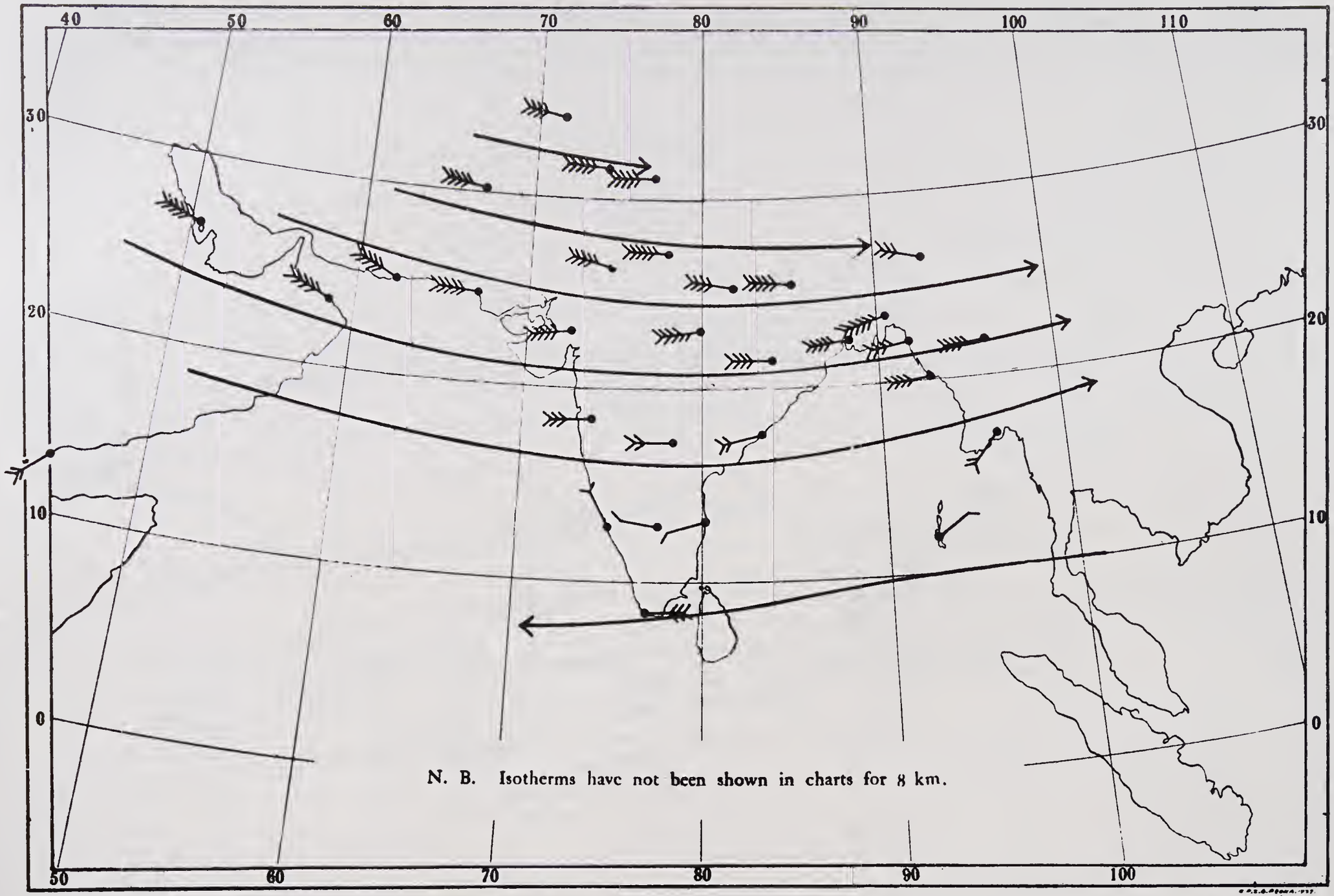
PLATE LXXII



UPPER WINDS AND TEMPERATURES OVER INDIA —— DECEMBER 4 KM.



UPPER WINDS AND TEMPERATURES OVER INDIA —— DECEMBER 6 KM.



N. B. Isotherms have not been shown in charts for 8 km.

UPPER WINDS AND TEMPERATURES OVER INDIA —— DECEMBER 8 KM.

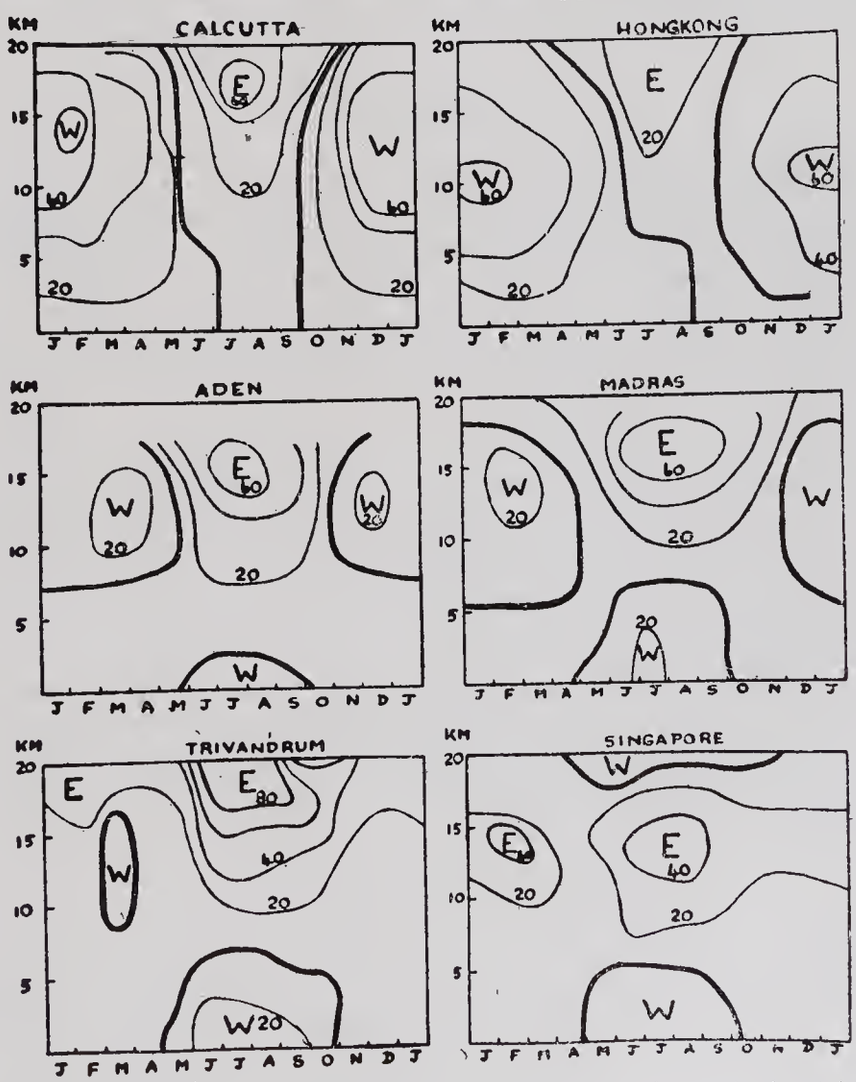
On Upper Tropospheric Easterlies and the Travel of Monsoon and Post-monsoon Storms and Depressions

By

K. R. Ramanathan
Physical Research Laboratory, Ahmedabad, India

Abstract

Aerological studies carried out from extensive networks of upper air stations particularly in North America and Europe have shown that the cyclones of middle latitudes are intimately connected with the undulations of the planetary westerly circulation and enabled us to trace the connection between the cyclonic vortices in the lower levels and wave-disturbances in the upper levels.



Upper winds over South Asia (wind speeds are shown in knots).

Proc. UNESCO Symp. on Typhoons, Tokyo, 1954, 243–244, 1955.

But our information regarding high level winds in the upper atmosphere over the tropics is yet too scanty. From the observation that are now available from Southeast Asia, North America, the Pacific and Australia, it is now clear that there is an easterly planetary circulation over the tropics and that waves form in this planetary stream. Indian meteorologists found in the high troposphere the easterly jet stream of the speed of nine knots in July and August over India.

Examples of tracks of cyclonic storms which crossed over from the China Seas across Indochina, Thailand and Burma from the east and re-generated in the Bay of Bengal are numerous. During the monsoon months, there occurs a succession of weather disturbances in the upper air moving one after another from the east across South Asia, and these, when they combine with an inflow of moist air from south of the Equator, develop into cyclonic storms of great extent but of feeble depth and contribute the major part of the rainfall of Burma, India and Pakistan.

It is most desirable to establish more radiosonde and radar-wind stations in the tropics.

Discussions

R. D. FLETCHER: In 1944-45, daily flights were made from Colombo to Australia and excellent in-flight observations were made on them. These showed up quite beautifully the band of west winds across the equator which also appears on Dr. Ramanathan's illustrations of cool-season maps as well as the lines of poor weather on both edges of the band. They also show up the value of data collected by aircraft. In agreeing with Dr. Ramanathan in the great need for data in the tropics, I'd like to point out the existence of civil air craft flying over many tropical areas. Flights of such aircraft should be utilized to provide meteorologists with much needed data.

G. S. P. HEYWOOD: I was much interested in Dr. Ramanathan's remarks about the SW monsoon. This airstream reached South China from the Indian Ocean in June, July and August, and sometimes penetrated as far north as the Yangtze. It was replaced from time to time during these months by Easterly winds from the Pacific. While the SW monsoon was flowing, there was no fear of typhoons affecting the South China coast, for they always come from the east, carried by the trade wind stream.

C. E. DEPPERMANN: I strongly approve of Dr. Ramanathan's idea of strengthening our meteorological reports in the tropics. In the second week of World War II, I published a brochure on upper air temperature, pressure and humidity of these Philippine region based only on data from Singapore, Manila, and Batavia. Unfortunately, every copy was lost in the War, but it was surprising how much valuable work could be done with only four stations strategically placed.

1

PROBLEMS OF TROPICAL METEOROLOGY AND THE RELATION BETWEEN THE CIRCULATIONS OF TROPICAL AND EXTRATROPICAL LATITUDES

K. R. Ramanathan (India)

1. The scientific basis of meteorology is the same, whether in the tropics or in the polar regions. But the tropics present special problems to the meteorologist, because they cover such a large part of the earth and, while the main source of energy of the atmospheric circulation is located there, the manner in which the energy of the absorbed solar radiation is transformed and converted into the energy of winds, zonal, meridional and as eddies can only be elucidated by reasoning based on extensive observation which is as yet available only in limited amounts.

Moreover, there is a seeming simplicity about the meteorology of the tropics, and the difficulties are hidden. The daily variations of temperature and pressure and of cloud formation and dissolution show up cellular and tide-like movements. Although some of the features of phenomena like the monsoons, tropical storms and easterly depressions are manifest at the surface and in the lower troposphere, the agencies controlling the movement of the disturbances are located higher in the atmosphere and observations of winds above clouds are as yet too few in the tropics.

The tropical tropopause is high and, during a large part of the year, there are strong upper easterlies whose maximum strength is reached generally at a higher level than that of the westerlies of middle latitudes.

Diagrams showing easterlies in the upper troposphere in different seasons prepared from radar observations made by the Indian Meteorological Department are shown in *Figs. 1* and *2*. For comparison, the upper wind data of Aden, Hongkong and Singapore taken from the publications of the scientific workers of the British Meteorological Service are also shown. The diagrams were prepared for me by my colleague Mr. K. P. Ramakrishnan of the India Meteorological Department.

2. Tropical storms originate in warm seas in the region of the upper easterlies and move in the general direction of the currents in the upper troposphere and their movement is no doubt governed by the same general principles as those governing the movement of storms in middle latitudes, with upper tropospheric divergence in advance of the cyclone, and convergence behind. They move northward when they meet anticyclonic blocks and recurve eastward when they come under the influence of eastward-moving troughs in the upper westerlies of higher latitudes.

Sci. Proc. Int. Assn. Met., IUGG 10th General Assembly, Rome 1954, 317–321, Butterworths, London, 1956.

3. Besides the fully developed tropical storms, there occur waves in the upper easterlies with which are associated feebler disturbances of a cyclonic character. Often during the monsoon months in S.E. Asia, two or three cyclonic disturbances are present at the same time, all moving westward; one may be in Indo-China, another over the head of the Bay of Bengal and a third over Kathiawar. A certain spacing (of the order of 20°) seems to be required to maintain their individuality. If the westermost depression meets an anticyclonic block, it either dies out or moves towards the northeast.

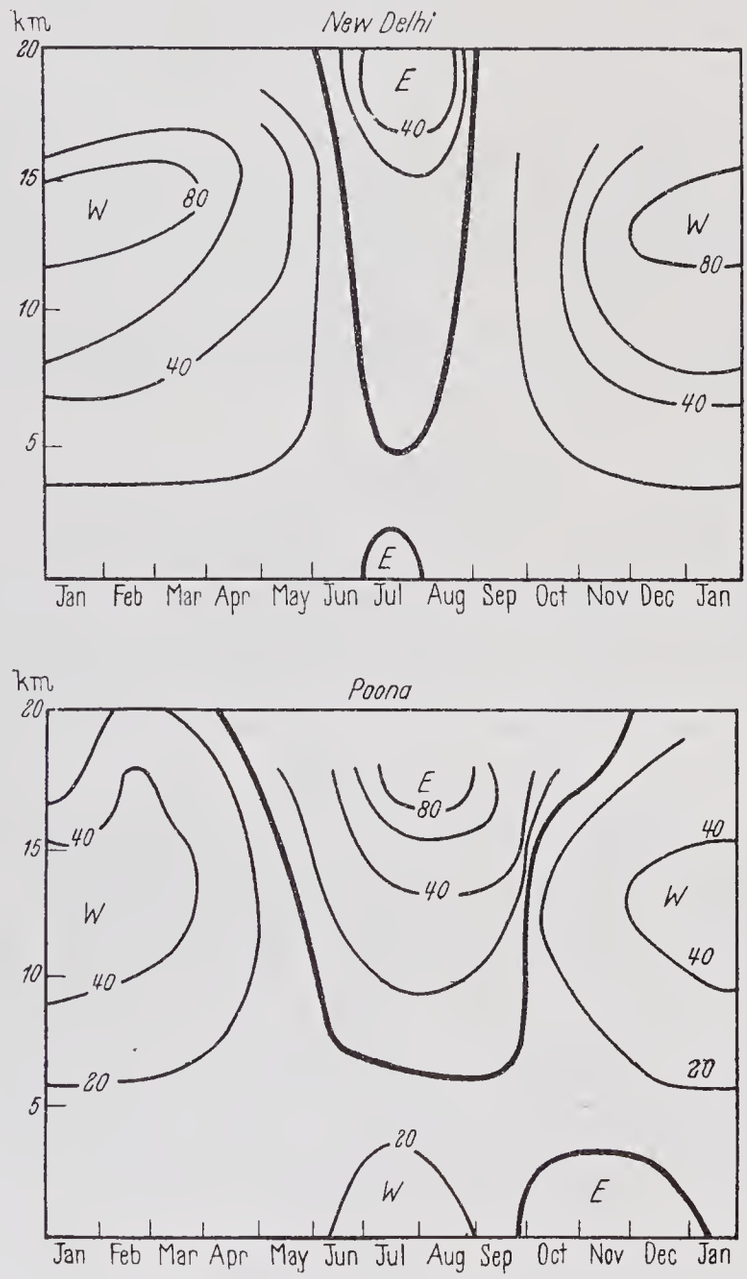


Figure 1

These disturbances are coupled to waves in the upper easterlies and often have large rainfall areas associated with them.

When the upper easterlies are well established over India, there is a regular succession of waves. Indeed, the monsoon is made up of these disturbances.

4. In the lower atmosphere, the moisture supply for the depressions during the monsoon comes from the southern hemisphere, generally in pulses. During the war, there were island observatories in the Indian Ocean at

Addu Atoll at 1° S and at Diego Garcia: they were very useful stations. Mr. MALURKAR[1] of the India Meteorological Department, who has given a good deal of attention to this problem, often noticed easterly waves in the upper air moving westward in the Indian Ocean south of the equator preceding a strengthening of the northward flow of air across the equator. The associated changes of pressure at sea-level were small.

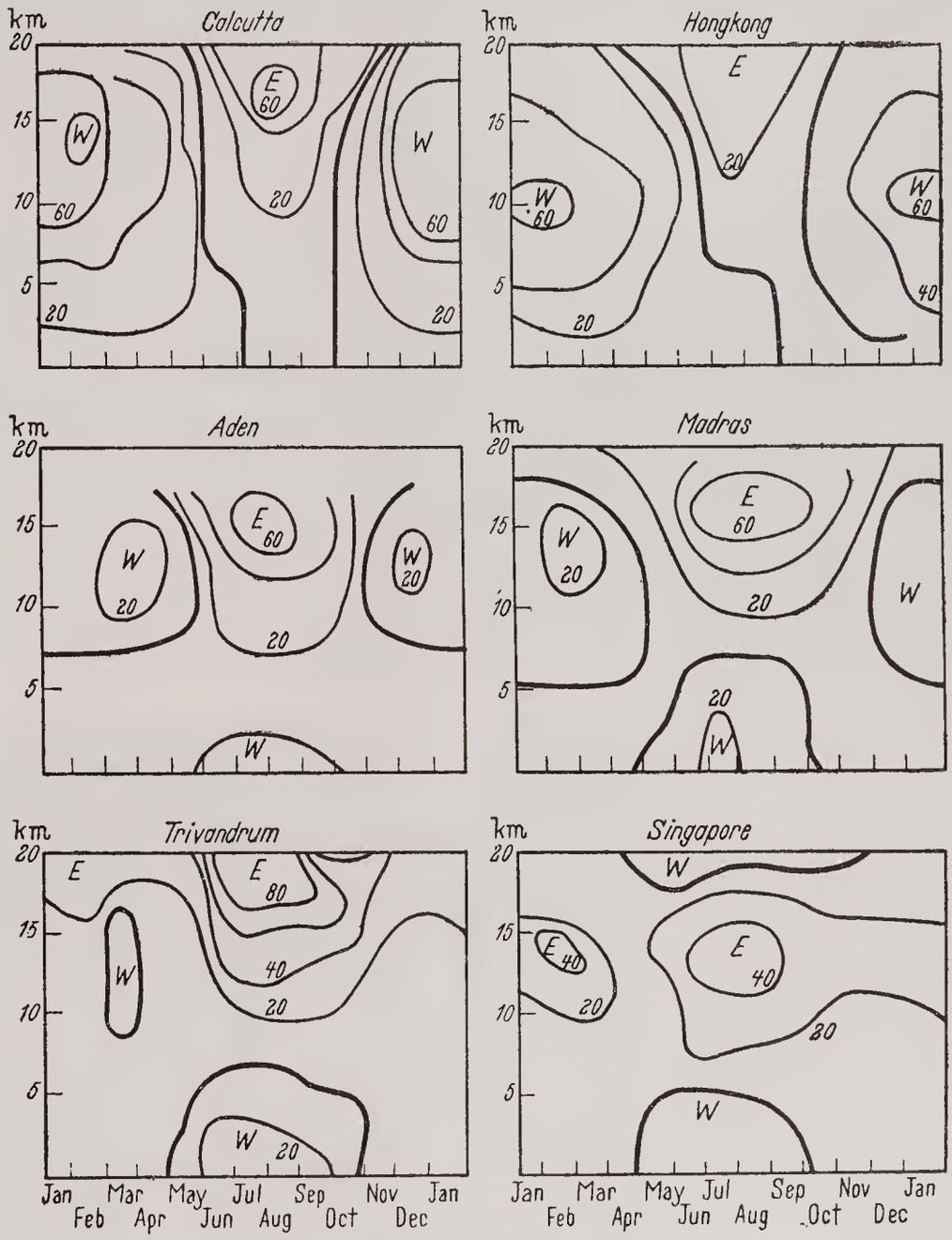


Figure 2. Upper winds over South Asia

5. The winter disturbances which move across N. India from December to April or May are wave-like disturbances in the upper troposphere. Not all of them cause clouding and rainfall. Southerly air at lower levels from the western side of the anticyclone is usually drawn in, but if this moist air originally formed part of the easterly stream at lower latitudes, the clouding and precipitation and vortex formation are more pronounced. Often, the upper wave above 6 km passes on, leaving a vortex in orographically favourable situation like the Punjab. These vortices gradually weaken and die.

6. The coupling of tropical depressions and storms and upper easterlies have been guessed at, but not established.

7. Studies of the movement of cirrus cloud and of winds[2] between 12 and 18 km over India[3, 4] show that even in seasons of generally clear weather, the movement in the upper troposphere is from SW to NE and E and rarely in the opposite direction. In the upper troposphere, the easterlies seem to feed into the upper westerlies of middle latitudes.

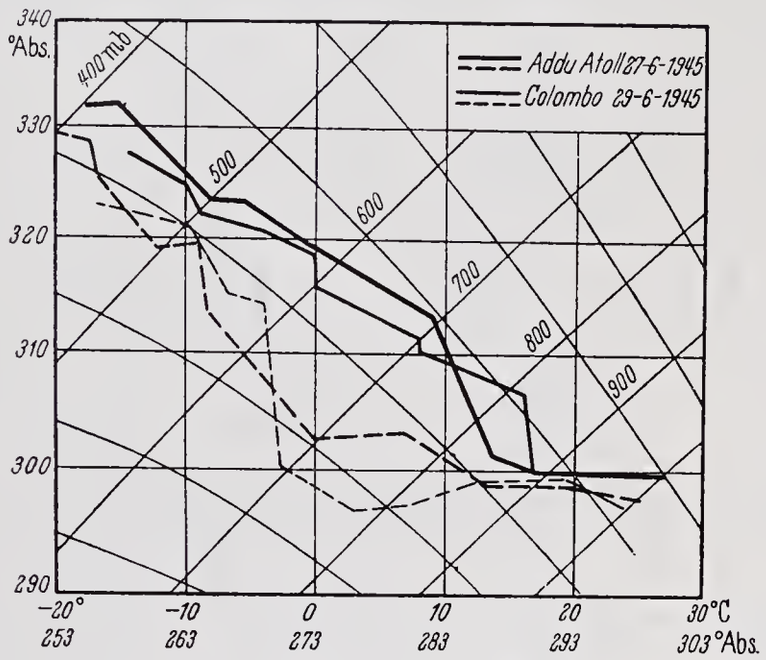


Figure 3

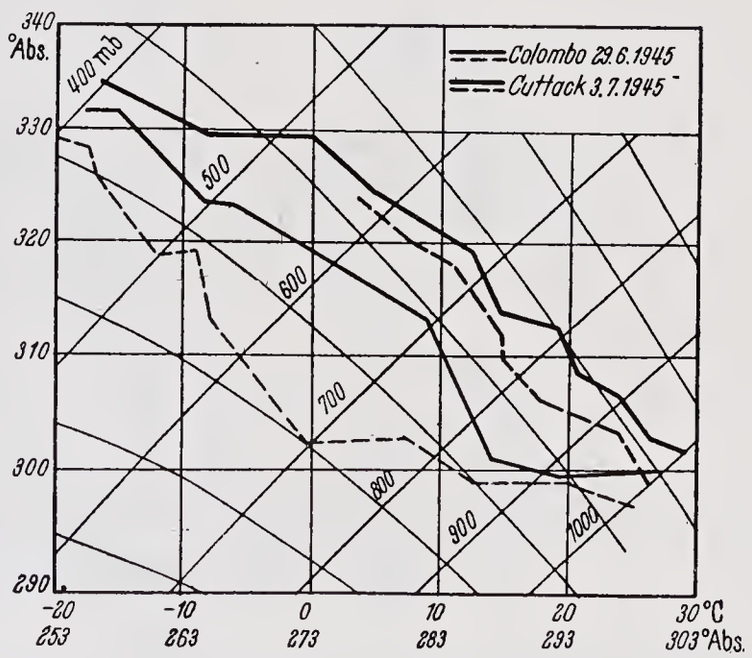


Figure 4

8. The trade inversion has been the subject of much study and is receiving further detailed attention from meteorologists in the U.S.A. It is a question of some interest to consider how the trades of the S. Indian Ocean transform into the monsoon of S. Asia. We do not know enough about it. Two diagrams prepared by Dr. Pisharoti are of interest in this connection. On crossing the equator, the monsoon current is less than 2 km deep. Typical

tephigrams of ascents at Addu Atoll and Colombo at the end of June are shown in *Fig. 3*, and the tephigram of upper-air conditions over Colombo and Cuttack (20° N) in *Fig. 4* for comparison. The deepening of the moist stream seems to take place north of the equator as a result of low-level inflow from the southern hemisphere, convergence and ascent into the upper easterlies which carry away the excess of air westward.

More detailed comparative studies of the structure of the atmosphere in trade and monsoon regions are called for.

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[1] MALURKAR, S. L., 'Analysis of Weather of India and neighbourhood' *Mem. Indian met. Dep.* 28 (1950) IV

[2] RAMANATHAN, K. R. and RAMAKRISHNAN, K. P., 'The general circulation of the Atmosphere over India and neighbourhood' *Mem. Indian met. Dep.* 26 (1939) X.

[3] VENKITESHWARAN, S. P., 'The upper winds at 10 km and above over India and its neighbourhood' *Mem. Indian met. Dep.* 28 (1950) II

[4] KOTESWARAN, P. and PARTHESARATHY, S., 'The mean jet-streams over India' *Indian J. met. Geophys.* 5 (1954) 138

Monsoons and the general circulation of the atmosphere — A review

K. R. RAMANATHAN

Physical Research Laboratory, Ahmedabad

ABSTRACT. While monsoons (or seasonal changes of wind and associated weather) occur in many different parts of the world, they are most pronounced over the countries of S. E Asia, Indonesia and Australia. Upper Wind Charts in January, April, July and October were shown to illustrate the large annual movement of inter-tropical convergence zones over the Indian Ocean as contrasted with those over the Pacific and Atlantic Oceans.

In the middle and high troposphere, the maximum S—N swing of the boundary region between the equatorial easterlies and the extra-tropical westerlies occurs over the Indian Ocean and bordering continent of South Asia.

The Asiatic Monsoon with its pattern of extensive seasonal precipitation and associated heating of the middle troposphere should be considered as exercising a very significant influence on the general circulation of the atmosphere. The Indian monsoon is a geographically bound cyclonic system less than 6 km in thickness embedded in the equatorial easterlies. The monsoon strengthens and weakens ; strengthens when there is fresh input of moist air and weakens owing to friction and dispersal of water-vapour. Associated with the monsoon are longitudinally-bound strong easterlies at 200 to 100 mb levels at about 15° N over South Asia. These strong easterlies form part of the equatorial easterlies, but are regionally accentuated.

Important questions such as long travelling waves and jets in easterlies and their role in creating and steering monsoon depressions, prolonged breaks in the monsoon and why they occur, world connections of the monsoon etc have been briefly referred to.

1. The word *Monsoon* is a modification of the Asiatic word "mawsim". It was applied by seamen navigating the Indian seas to the annual alternating winds of the Arabian Sea. It is now generally applied to quasi-stationary disturbances of the average zonal circulation, particularly in the tropics, arising from temperature and humidity differences between continental and oceanic areas and between the northern and the southern hemispheres. They are best developed in the summer season of either hemisphere, *i. e.*, in July-August or in January-February. Fig. 1 shows the surface air streams and the approximate boundaries of separation between the air streams of the northern and the southern hemispheres in January and July (after Sawyer, 1952). In July, while over a large part of the Pacific and Atlantic oceans, the inter-tropical boundary lies a little to the north of equator, the southern hemisphere air-stream penetrates well into the northern hemisphere in India and southeast Asia and to a smaller extent in Africa. In January, the northern hemisphere streams penetrate farthest southward in South America (Brazil), East Africa and Northeast Australia. These areas of extensive (penetration of air from the colder into the warmer hemisphere and continents are the main monsoon areas. I am, however, not sure that the term monsoon is used in South America.

Proc. Symp. Monsoons of the World. New Delhi, 53–64, 1958.

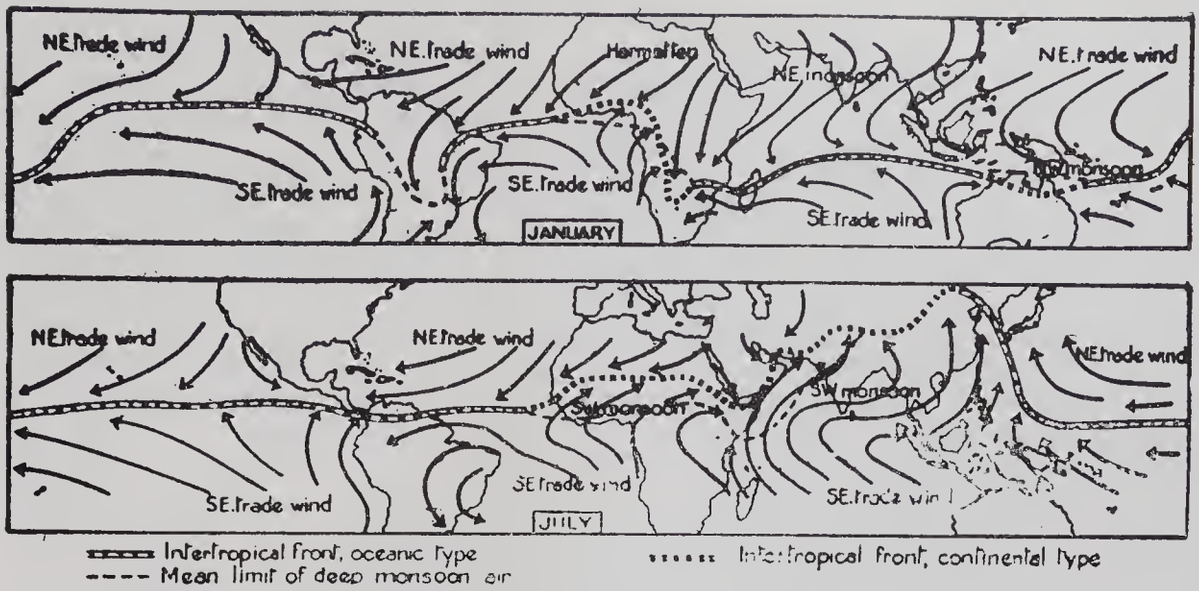


Fig. 1. Inter-tropical Fronts and Surface Air Streams in January and July (J. S. Sawyer)

2. The Asiatic monsoon is the best known of the monsoons. It is vitally important for food production in India and the countries of Southeast Asia ; a good deal of attention has, therefore, been paid to its study from the beginning of scientific meteorology in India. The space and time variations of rainfall during the monsoon, the disturbances and the storms associated with it—the breaks or failures in the monsoon, the forecasting of monsoon rains, all these have received attention. The study of upper air temperatures and humidities, and of winds up to the stratosphere, in India and neighbouring countries, have helped to link up the atmospheric circulation over India with that over the rest of the world.

3. The Indian Ocean is mostly an enclosed area with Africa on the west and Asia on the north. It is partly enclosed on the east by Australia and the Eastern Archipelago and is open towards the Antarctic. The existence of open seas right from the Tropic of Cancer to Antarctica, of Africa and Eurasia to its west and north with the lowest pressures over the region Arabia to W. Pakistan, and of the Himalayan and Burmese mountain systems are responsible for the exceptional build-up of the Asiatic summer monsoon.

In a classical paper on the Indian southwest Monsoon, Simpson (1921) treated the problem of the Indian summer monsoon as that of an extensive closed heat low, orographically bound. He laid special emphasis on the role of the Himalayas and the Burmese mountains in containing most of the moist air within the confines of India and Burma and increasing their rainfall. Petterssen (1953) in a recent paper "On the dynamics on the Indian Monsoon" while fully realising the importance of perturbations of the monsoon, considered it worthwhile to discuss the problem of maintaining the observed large scale cyclonic system in a steady state by creation of vorticity by thermal processes and destroying it by friction within a closed system. These studies have illuminated some of the fundamental aspects of the problem.

Working meteorologists are, however, aware that the average monsoon of climatology in any particular month is a complex composite of many different kinds of weather situations. The average monsoon is continuously subject to perturbations and many of these perturbations are induced by causes originating outside the closedsystem.

4. In 1948, a volume of Climatological Charts of the Indian Monsoon Area prepared by the author and Mr. S. P. Venkiteshwaran was published by the India Meteorological Department. In that volume, a large amount of information about winds and isobars, upper winds upto 3 km, rainfall amounts over land areas, percentage hours of occurrence of rain over the seas and typical tracks of storms in the Indian Ocean and the surrounding areas was collected from various sources and put together for each month of the year. Other publications of the Department give information about winds and temperatures at higher levels. It was thought that it would be of interest to give here in a slightly modified form the monsoon area charts for the surface and for 3 km for the months of February, April, July and October (Figs. 2-5). Inter-tropical convergence boundaries are marked on the surface charts, and boundaries or regions of westerly winds on the 3-km charts. A study of the rainfall lines over land and sea shows that in the *tropics* 0-2, 2-5, 5-10, 10-20 and 20-30 percentages of occurrence of rainfall over sea is roughly equivalent to 0-2, 2-5, 5-10, etc, cm of rainfall in a month. The *extensive* heavy rainfall in July (and August) in India, Southeast Asia and the adjoining seas over a large range of latitudes and longitudes is especially noteworthy. It implies release of a large amount of latent heat in the atmosphere at the levels of condensation, and upward flux of heat at higher levels.

An important feature brought out by the upper air streamlines is that almost in all the months, the inter-tropical convergence zone over the ocean has a considerable width, the southeast trades of the southern hemisphere and the northeast trades of the northern hemisphere tending to become westerlies near the region of convergence even at 3 km. Naturally, the stream that crosses the equator has a greater tendency to become westerly.

The upper westerlies are more pronounced during the summer monsoon months July-August, when they are almost entirely on the northern side of the equator. In their northwestern part, the westerlies at 3 km have more and more of the northern hemisphere dry air in them.

In January-February, the inter-tropical convergence zone lies to the south of the equator, and the westerlies are more pronounced in the eastern half of the South Indian Ocean and the regions of East Indian Archipelago and North Australia where there is a monsoon low.

The effectiveness of the summer monsoon of India and Indonesia, from the point of view of rainfall, is undoubtedly due to the development of thick, moist columns of air (5-6 km at their thickest) before they meet stationary or moving obstacles.

All tropical monsoon circulations are topped by equatorial easterlies, but the easterlies are substantially modified by the monsoon.

5. *Upper Air conditions over the Asiatic Summer Monsoon*—From the days of the sounding balloon ascents at Agra, it has been known that the highest average air temperatures in the world between 6 km and 13 km are found during the summer monsoon over North India. It is possible that still higher temperatures may be found over Northeast Himalayas and South Tibet. From the meridional profiles of pressure in northern summer and winter over Eurasia (Fig. 6 after Bjerknes), it is evident that while in July-August, the lowest pressure at the surface is found at about 25°N with a pressure gradient

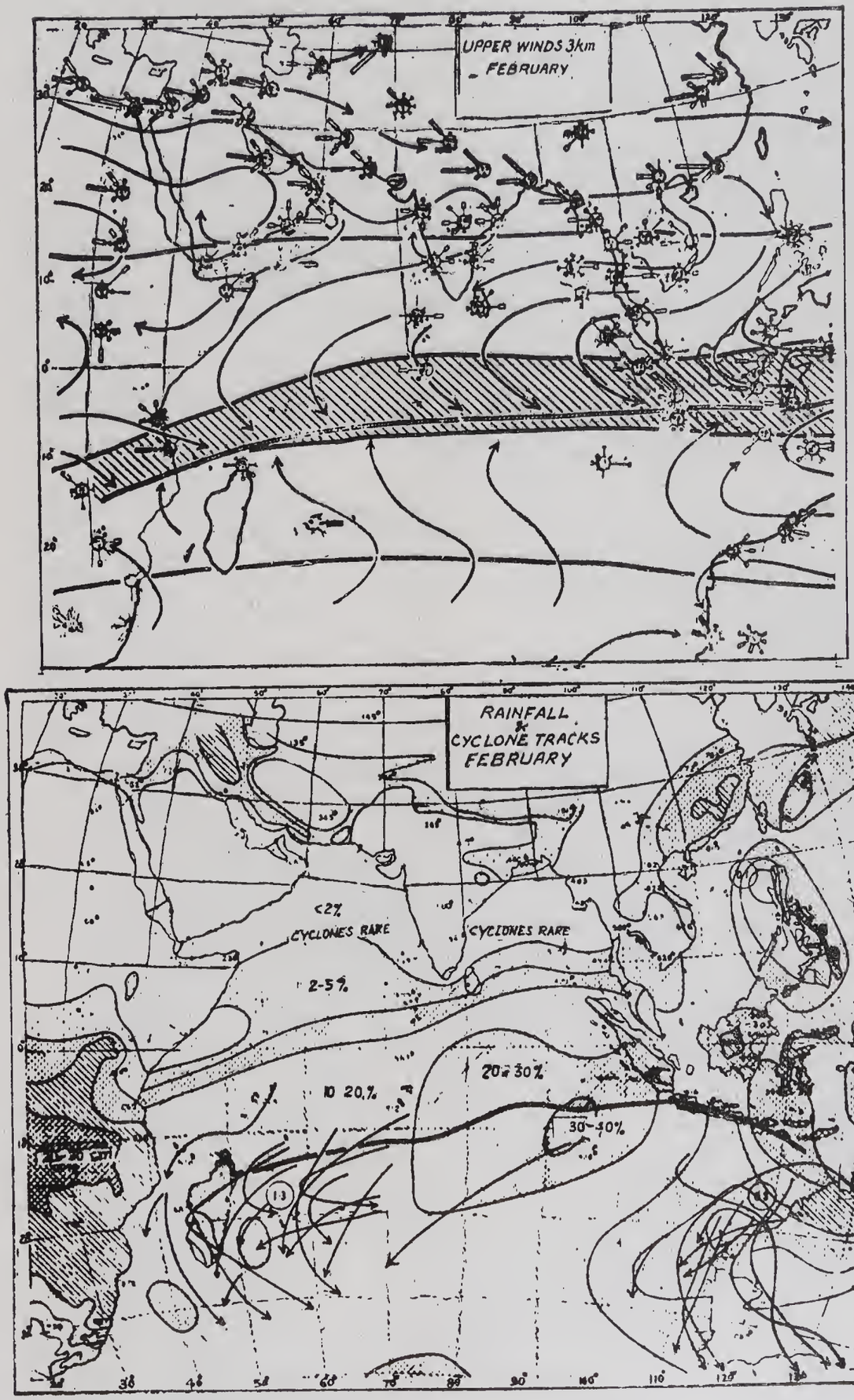
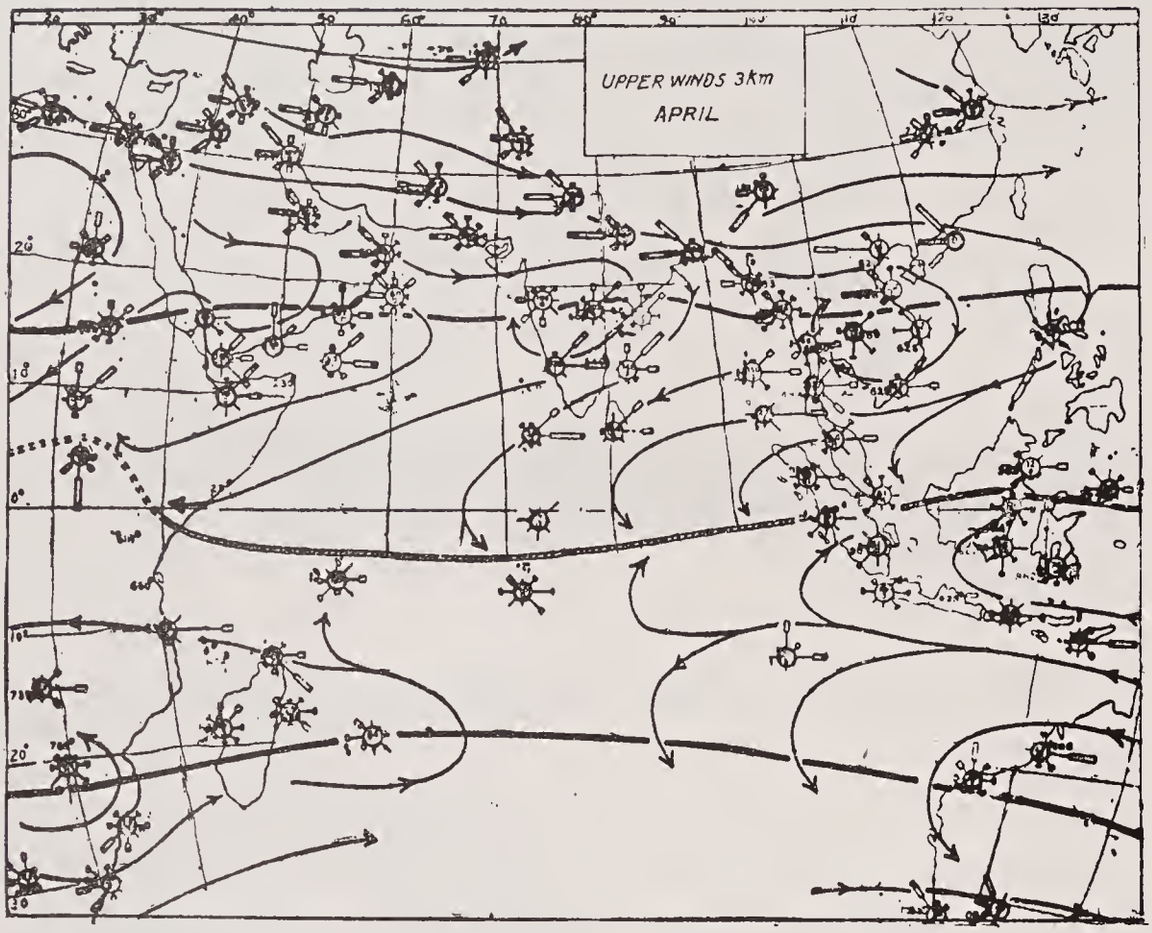
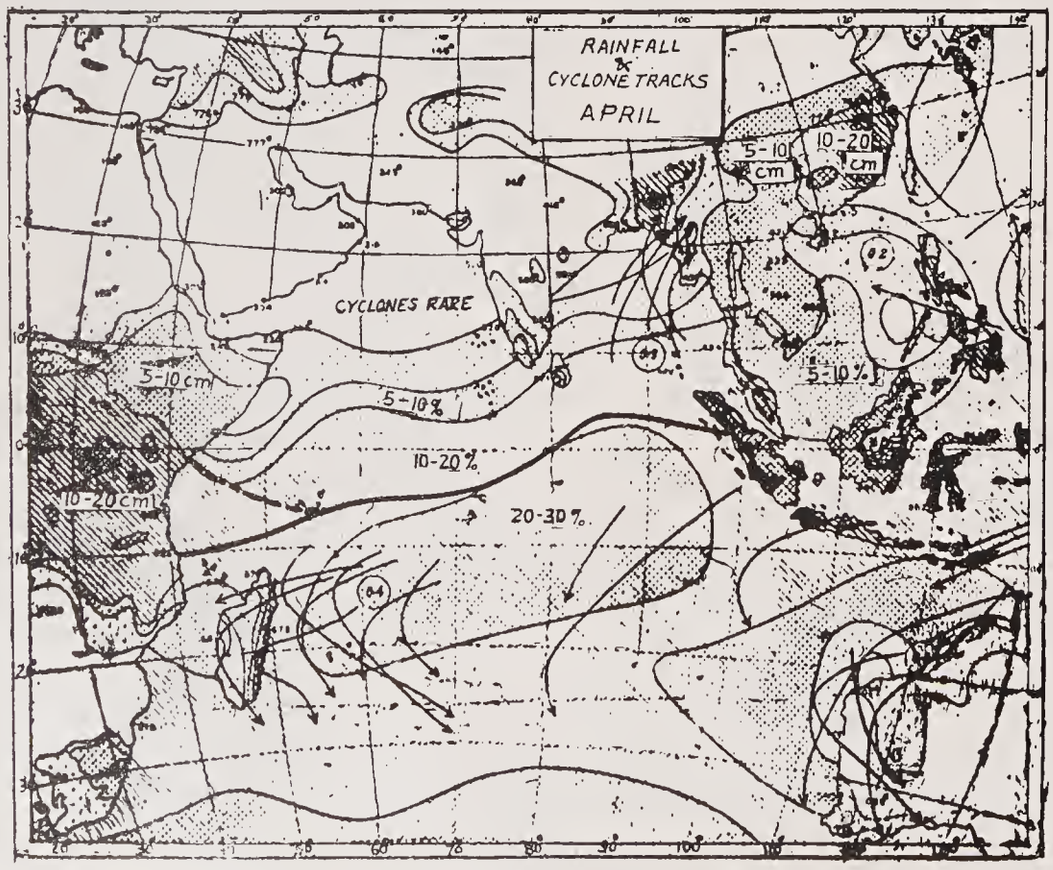

UPPER WINDS 3km
FEBRUARY
RAINFALL
CYCLONE TRACKS
FEBRUARY
<2%
CYCLONES RARE
CYCLONES RARE
2-5%
10 20%
20-30%
30-40%

Fig. 2


UPPER WINDS 3km
APRIL


RAINFALL
&
CYCLONE TRACKS
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5-10 cm
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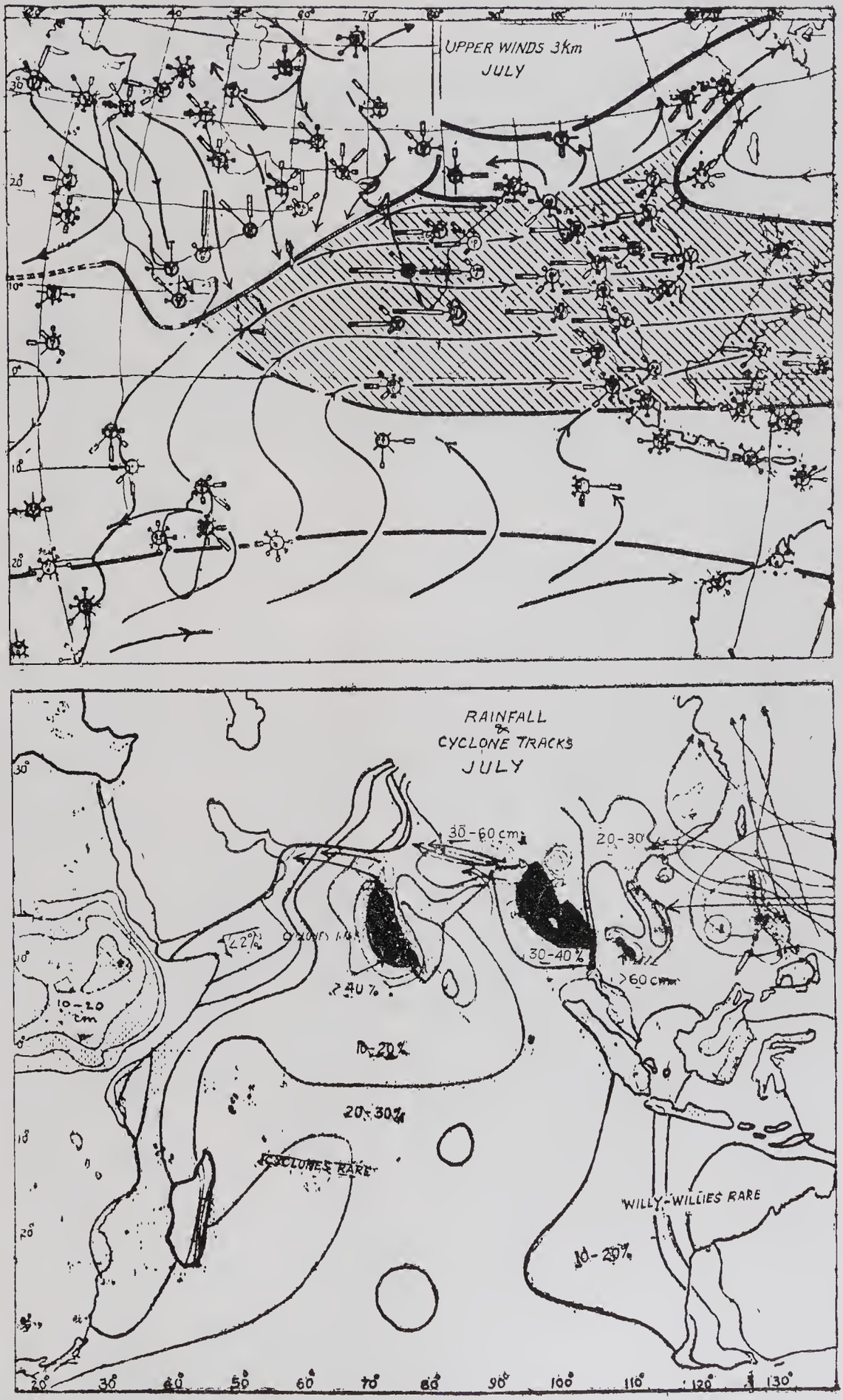
Fig. 3


UPPER WINDS 3Km
JULY
RAINFALL
&
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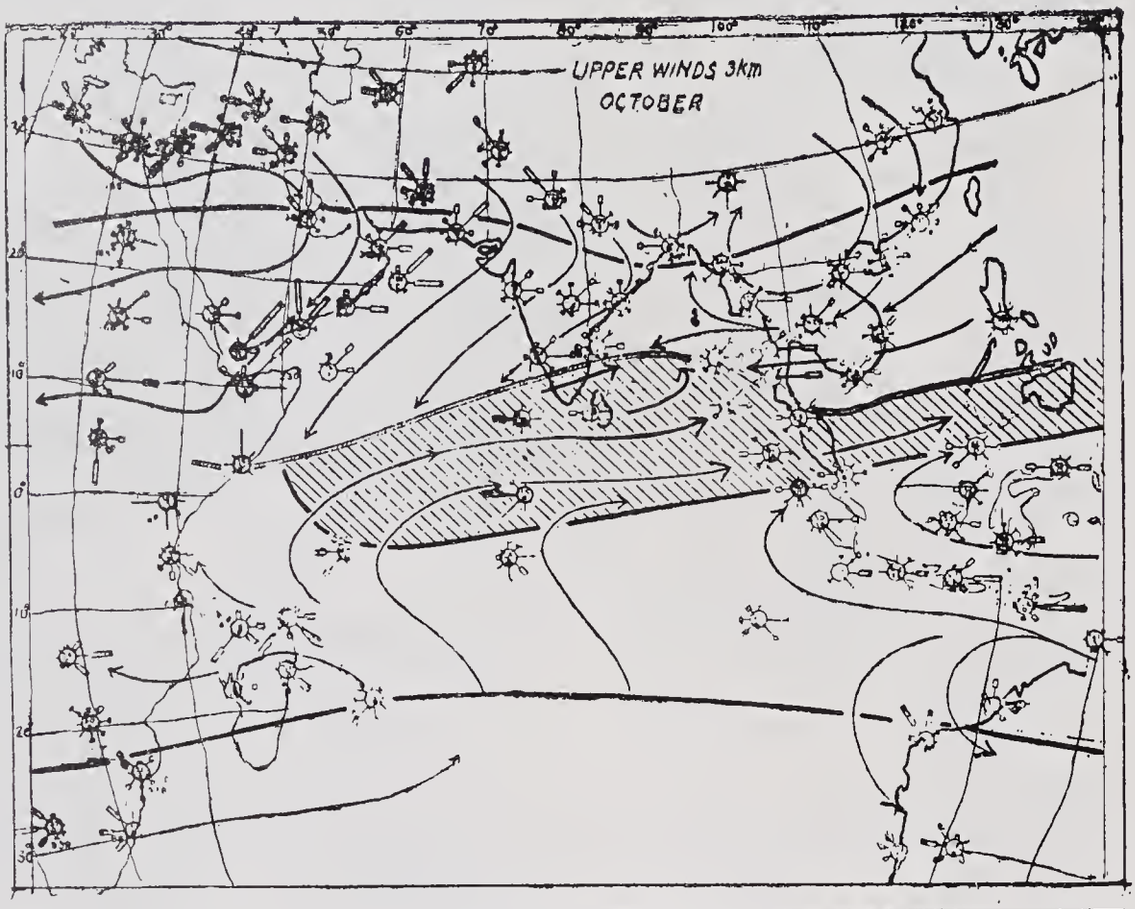
JULY
30-60 cm
20-30
30-40%
>60 cm
10-20 cm
10-20%
20-30%
CYCLONES RARE
WILLY-WILLIES RARE
10-20%

Fig. 4


UPPER WINDS 3km
OCTOBER

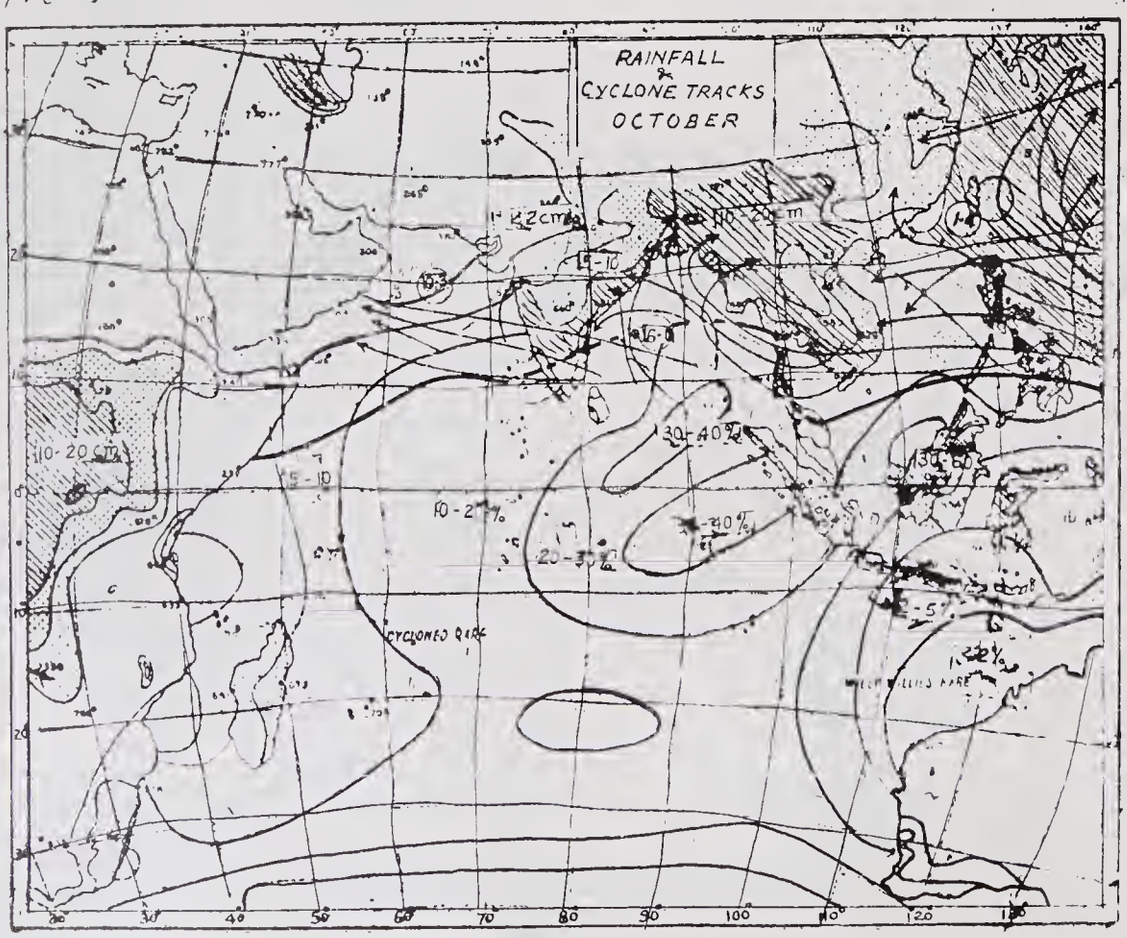

RAINFALL
&
CYCLONE TRACKS
OCTOBER
10-20 cm
30-40 %
CYCLONIC CIRC

Fig. 5

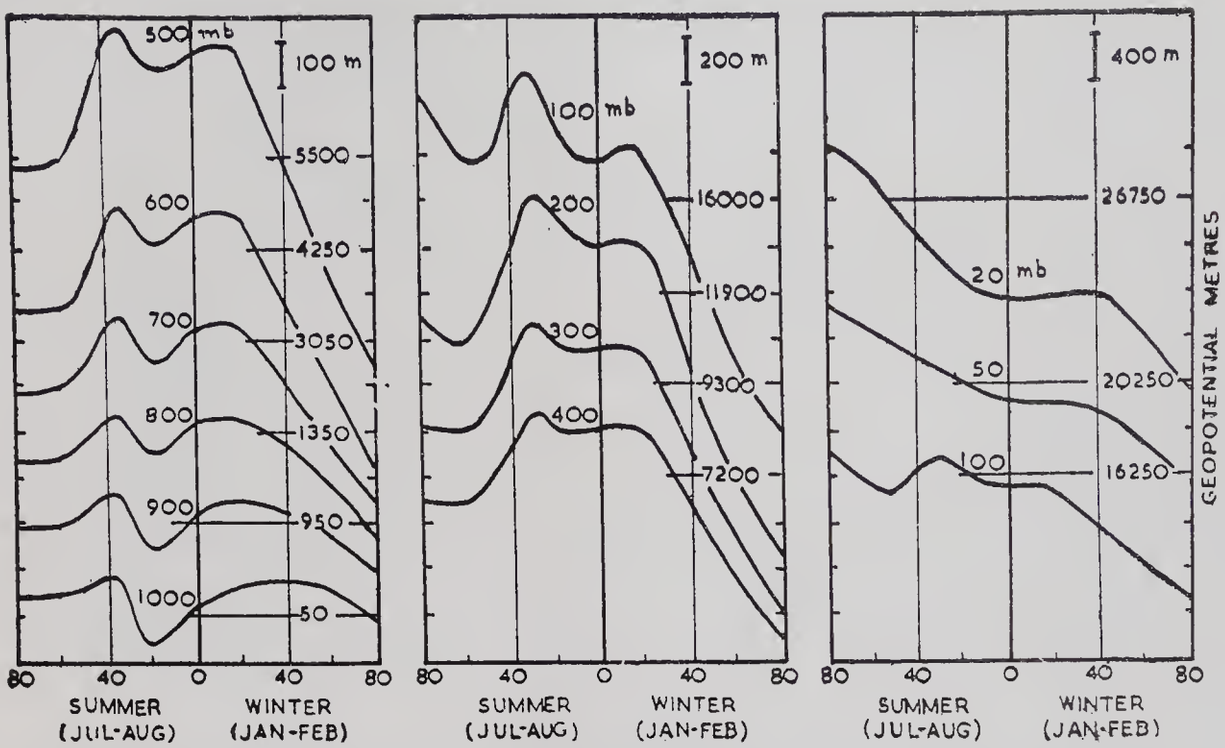


Fig. 6. Meridional profiles of isobaric levels in Northern Hemisphere in summer and winter

from the southern hemisphere, the trans-equatorial gradient vanishes at a height of about 400 mb. From 300 to 100 mb, the highest pressures are found at 25-30°N with strong equatorward gradients. These pressure profiles are based on the upper air temperature data of Agra, Poona, Madras and Batavia and therefore represent conditions over the monsoon area. The upper easterlies which have been observed in strength above 10 km and into the stratosphere over India (and South Asia generally) are consistent with these pressure profiles (Venkiteshwaran 1950, Frost 1953, Krishna Rao 1952). In winter, the anticyclonic ridge is much less pronounced and nearer the equator.

6. Since the introduction of radio-wind observations, daily data of high level winds have become available at a few stations over India also and the changes in strength of these upper easterlies at 10°-20°N have come in for more detailed study from Indian meteorologists and in particular from Koteswaram and his co-workers. As Koteswaram (1958) has pointed out, the strong easterly winds near the tropopause in summer are a special feature of the Asiatic monsoon region and are not to be found over the Atlantic or the Pacific. They seem to be coupled to the deep westerly winds of the lower troposphere. The upper easterlies sometimes take the characteristics of jet streams. Thus, the pressure and wind profiles over the Asiatic monsoon region in summer differ in important respects from those over other longitudes.

Questions of some interest are as to how these strong upper easterlies are produced and maintained in summer, and as to their role in the development and movement of disturbances. The location of the high level anticyclonic cell over the Pacific and East Asia and its strength and orientation are important factors in determining these easterlies. The highest pressures above 8 km are found over regions of extensive heavy rainfall and downstream regions at these high levels. The physical reason for this is that temperatures over regions of extensive heavy rainfall tend to follow the saturation adiabat.

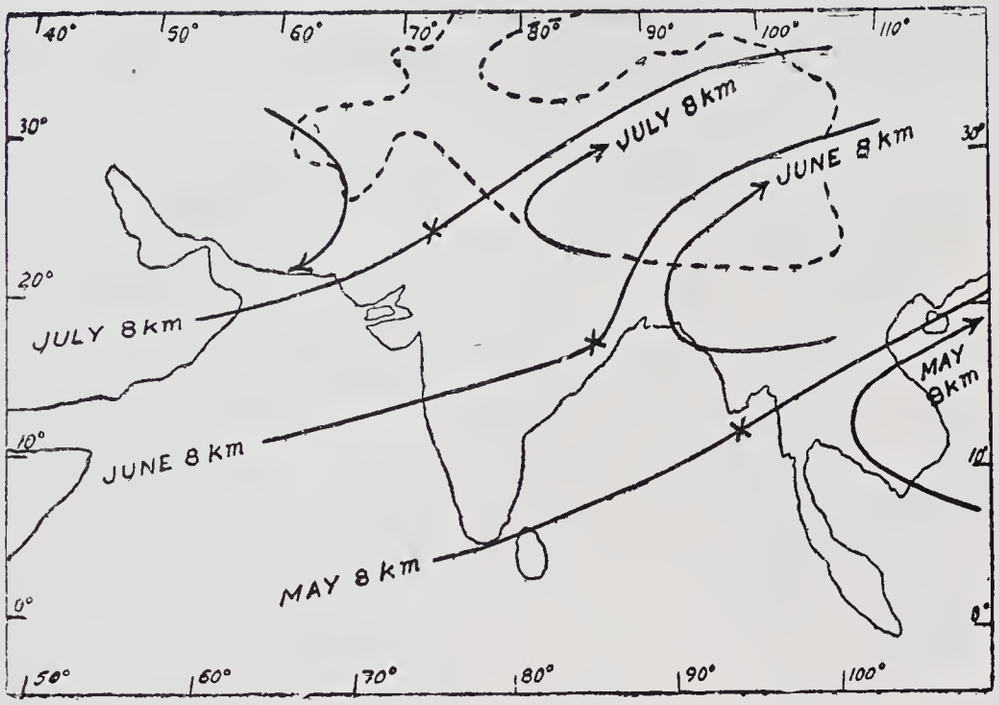


Fig. 7

After traversing an extensive rainfall area, air at upper levels will tend to cool by radiation and subside, but over unclouded or partly clouded areas and particularly over high plateaus, ground heating will reduce the subsidence. Moreover, air which has subsided rapidly will itself be warmer.

If we study the mean upper winds at 8 km and above over South Asia in the months April to August, we find that at 8 km in April, the westerlies are regularly observable down to 15°N and the winds are mainly zonal. In May, a col appears at about 15°N, 95°E between the African—West Asian anticyclonic cell on the west and the Pacific—East Asian cell on the east. In the next two months, the col moves rapidly towards the northwest. It is at about 21°N, 86°E over the Orissa coast in June and near 29°N, 74°E over north Rajasthan in July and August. On the western side of the col, air flows from north to south, while on the eastern side, it flows from south to north. The approximate partition lines between the air of westerly origin and that of easterly origin at 8 km in each of the months, May, June and July are shown in Fig. 7. These are based on pilot balloon data. If winds could be had on cloudy and rainy days also, it is very likely that the lines will be displaced towards the west and north. The explosive northward push of the warm moist air from May-June is remarkable. At levels higher than 8 km, the Pacific easterlies gain dominance over the West Asian—African easterlies and spread westwards and northwards. The northwestward movement of the col and the increase in strength of the upper easterlies are linked with movement of the major tropical rainfall areas from South Burma—Indo-China and adjoining Pacific, first to Burma proper—NE India and South China and later to middle and West Himalayas and to North India generally (due to moving depressions). It may also be remembered that the southeast monsoon over China fed by moist air from the Pacific extends the rainfall area northeastward from Northeast Himalayas to Korea and Japan.

The net result of the changing rainfall distribution will be to strengthen the western portion of the Pacific anticyclone in the upper troposphere with a tilt towards the northeast. The air coming out of this elongated high level anticyclone towards lower latitudes will continuously bring easterly momentum at higher levels.

TABLE 1

	1948	1949	1950	1951	1952	1953
1. First appearance of easterly winds over Aden at 200 mb	—	May 18	May 19	May 25	May 12	May 22
2. End of polar type tropopause over Habbaniya	Jun 9	May 27	May 22	May 26	Jun 1	Jun 11
3. Start of monsoon on Malabar coast	Jun 10	May 23	May 27	May 31	May 28	Jun 7
4. First appearance of easterlies over Bahrein at 200 mb	Jun 15	Jun 13	Jun 10	Jun 13	Jun 8	Jun 20

The rainfall which depends on the moist air inflow of the monsoon winds at lower levels and their ascent is thus an important agent in changing the position and strength of the warm subtropical high level anticyclone to the north of the monsoon area and correspondingly of the high level easterly winds over South Asia, and indirectly in guiding the movement of monsoon depressions and storms.

7. An interesting association of upper air changes near the tropopause over the Middle East with the beginning of the Indian summer monsoon was pointed out by Sutcliffe and Bannon (1954). In Table 1 are given the dates of onset of the monsoon on the Malabar Coast in the years 1948 to 1953 with marked sudden changes in conditions aloft over Aden, Bahrein and Habbaniya.

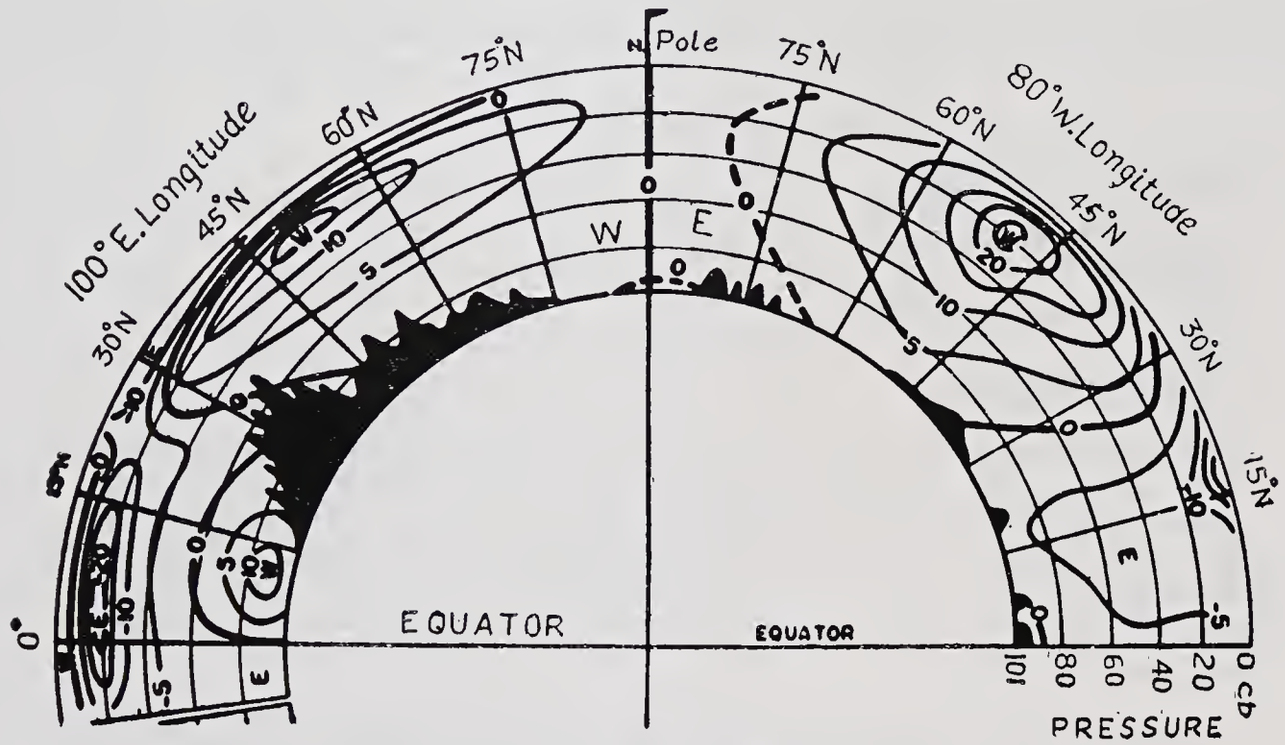
It is interesting to note that the appearance of the upper easterlies over Aden precedes the onset of the monsoon on the Malabar coast by 5 to 16 days. The replacement of westerlies by easterlies is so sudden and occurs at such high levels that the change cannot be attributed directly to solar heating of ground layers. It is worth examining the corresponding dates of beginning of heavy rainfall on the Tennasserim coast. The easterlies reach their maximum development in July in India and August in Singapore.

8. Meridional wind sections in July are available for 80°W (America), 45°E (East Europe-Arabia), 75°E (India), 100°E (East Asia), 140°E and 170°E (Pacific), and British meteorologists have produced maps of upper winds at different levels up to 60 mb (Bannon and Jones 1956). In the lower troposphere, there are no westerlies in America or the Pacific. The westerlies are deepest (about 6 km at 10° to 15°N) over India and East Asia. The African monsoon produces westerlies of about 2.5 km thickness over West Africa and Sudan. Meridional sections of winds over 100°E and 80°W in July and January prepared by Y. Mintz are shown in Fig. 8. They bring out clearly the influence of the Asiatic monsoon.

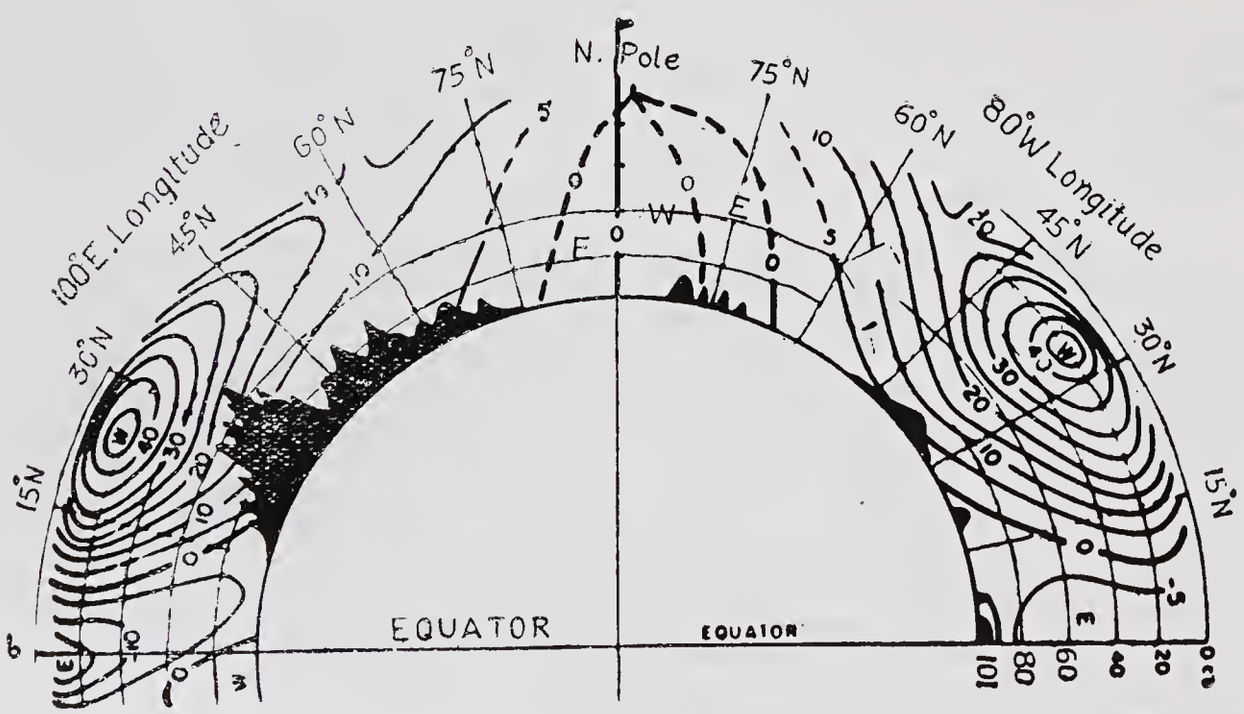
9. *Disturbances of the monsoon*—I shall make only a few brief remarks on this. In July and August, low pressure waves or depressions form with some regularity at the head of the Bay and travel towards the west or west-northwest. These depressions are very efficient agents for spreading rainfall over a large part of the country. Generally associated with the formation and movement of these depressions are two important phenomena —

(1) Strengthening and advance of the moist monsoon current from the southwest or west ;

(2) Arrival of high level easterly waves at the head of the Bay from the east across Burma and their travel westward. It has not been



MERIDIONAL WIND SECTIONS
100°E AND 80°W-JULY



MERIDIONAL WIND SECTIONS
100°E AND 80°W-JANUARY
(Y. MINTZ)

Fig. 8

established that these waves are *essential for the formation* of depressions. Their precise role requires further elucidation.

A third phenomenon which sometimes occurs and is of great interest is a "break" in the monsoon. This happens when a low pressure area appears over Tibet and the easterly winds of the Gangetic valley are replaced by winds from the northwest. Breaks often cause heavy rainfall over Northeast Himalayas.

Study of upper air conditions over USSR and China are required for the elucidation of this important phenomenon.

These three phenomena link up the Indian monsoon (1) with the Trades of the South Indian Ocean, (2) with the so-called equatorial upper easterlies and the sub-tropical high over the Pacific and (3) with the extra-tropical westerly circulation north of the Himalayas.

10. *Monsoon Seasonal Forecasting*—India is the home of seasonal forecasting. An excellent summary of the beginnings and growth of this subject and of its present status is available in the Presidential address of Sir Charles Normand to the Royal Meteorological Society in 1953. Not much change has happened since then. I may draw attention to two important remarks contained in it.

(1) The most remarkable of Walker's results was his discovery of the control that the Southern Oscillation (the tendency for air to be removed from the Pacific area Tokyo to South America and its simultaneous accumulation in and around the Indian Ocean) exerted upon subsequent events, and

(2) The Indian monsoon has closer connections with later events elsewhere rather than with earlier events.

The physical basis for the Southern Oscillation has yet to be found.

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(Contd. from front flap)

Also included are his papers on night airglow and the ionospheric effects of X-ray from the sun and from discrete galactic sources.

Many of these papers were published in different journals in many parts of the world and in the Scientific Notes and Memoirs of the India Meteorological Department, not readily accessible to present day workers in the field. These volumes, in which are collected Professor Ramanathan's important, original contributions to a wide range of subjects, should find a place in the libraries of all those interested in optics, meteorology and geophysics.

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